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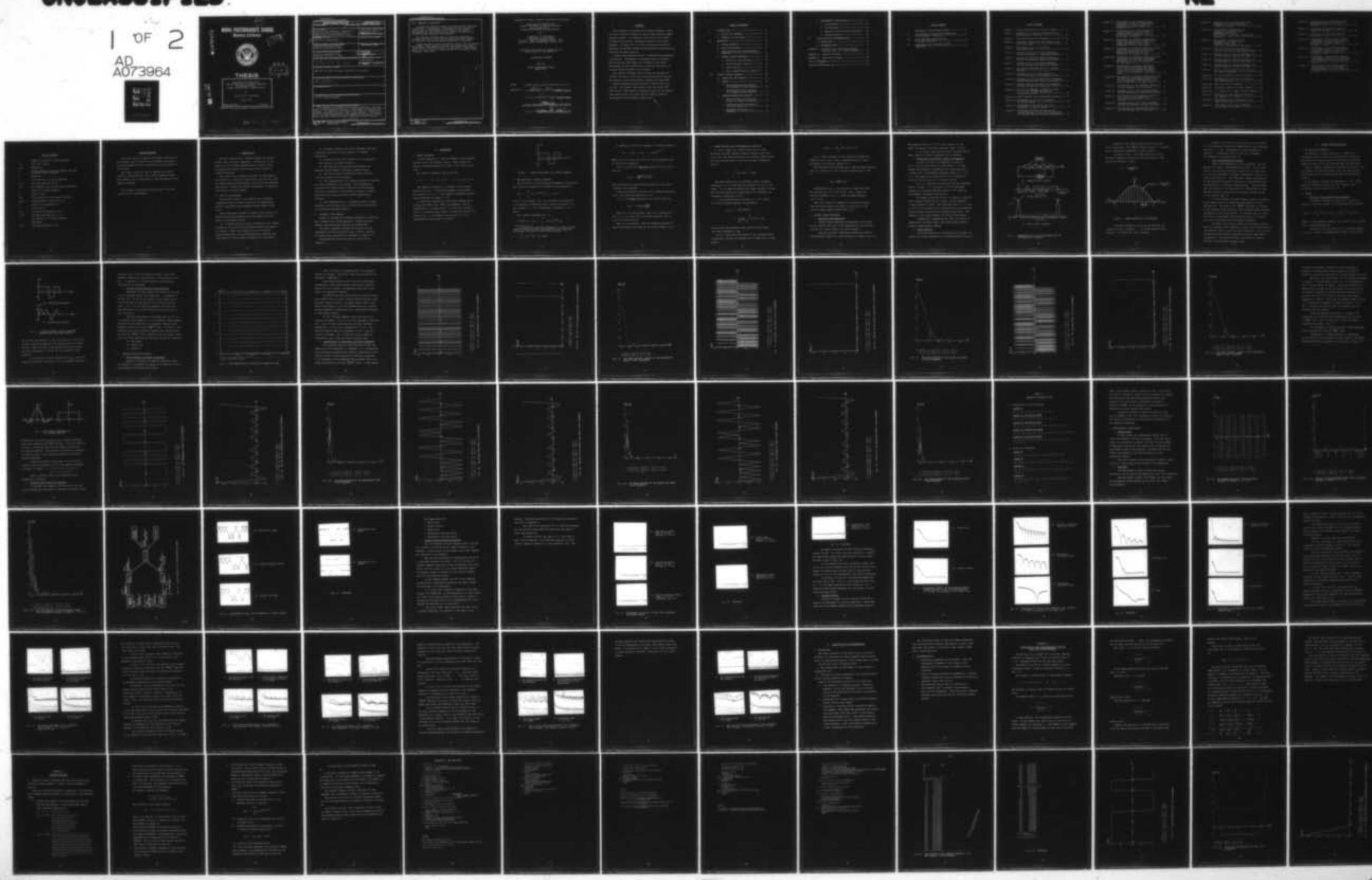

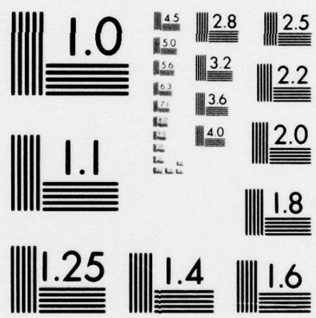

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THESIS

TECHNIQUES AND BENEFITS OF
SHAPING THE PULSES OF BINARY SEQUENCES
WITH APPLICATION TO
SPREAD SPECTRUM RADIO COMMUNICATIONS

by

Panayiotis G. Mavraganis

March 1979

Thesis Advisor: G. Myers

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This research is concerned with binary sequences. Such two-level voltage waveforms are used in some types of spread spectrum systems. Of interest in this work is the effect of shaping the normally rectangular pulses of the binary sequence. An objective is to find and tabulate particular sequences and specific shapes having desirable autocorrelation functions and power spectra.

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#20 - ABSTRACT - CONTINUED

A direct and versatile method of shaping binary sequences is presented. Photographs of sequences having triangular, raised sine and ramp shapes are included in the report. Photographs of the autocorrelation function and spectra of selected shaped sequences are presented.

The computer programs used to search for sequences of interest and used to calculate the autocorrelation function and spectra of particular shaped sequences are described.

Shaped sequences having interesting spectra were discovered. For example, some spectra have very small side lobe levels; others have no discernible nulls in the spectra; some spectra have nulls which are not simply related to the sequence clock frequency (pulse rate).

Techniques and Benefits of Shaping the Pulses of Binary Sequences with Application to Spread Spectrum Radio Communications

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ELECTRICAL ENGINEER

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March 1979

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This research is concerned with binary sequences. Such two-level voltage waveforms are used in some types of spread spectrum systems. Of interest in this work is the effect of shaping the normally rectangular pulses of the binary sequence. An objective is to find and tabulate particular sequences and specific shapes having desirable autocorrelation functions and power spectra.

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LIST OF SYMBOLS

n	Number of stages of a shift-register
$v(t)$	Two level voltage
$v_s(t)$	Shaped $v(t)$
A	Binary sequence A (capital letters are used to denote binary sequences)
B	Bandwidth
E	The envelope of the power spectrum
$G_v(f)$	The power spectrum of $v(t)$
$I(f)$	The imaginary part of the Fourier transform
L	Length of a binary sequence
P	Power in watts
$R(f)$	The real part of the Fourier transform
$R_{vv}(\tau)$	Autocorrelation function of $v(t)$
T	Period of the sequence $v(t)$
V	Value of $v(t)$
$V(f)$	The Fourier transform of $v(t)$
$\|V(f)\|$	The amplitude spectrum of $v(t)$
ε	Bit duration of a binary sequence
τ	Time delay
$\theta_v(f)$	The phase spectrum of $v(t)$

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The author would also like to express his sincere thanks to LCDR Steve Hall, USN, former Computer Science staff member, for his assistance in the development of the computer programs.

This thesis is dedicated to my wife Aliki, for her great help and understanding.

I. INTRODUCTION

The work reported here concerns shaping the voltage pulses (bits) of binary sequences. An objective of the study is to find binary sequences having spectra which, by proper pulse shaping, can be made nearly uniform or otherwise modified.

This report also includes the theory of pulse shaping, the results of a computer investigation, the circuitry used to generate desired pulse-shapes, and the time and frequency descriptions (voltage and spectra photographs) of sequences with pulses of various shapes.

A. PLAN OF THE RESEARCH

The two main areas of this research are a computer investigation and the design and use of an experimental system to generate binary sequences having shaped pulses (bits).

Three steps were followed in pursuing the objective of identifying binary sequences and pulse shapes that have nearly uniform power spectra.

(1) A computer search for binary sequences of all lengths through 20 bits to find those sequences which have spectra of interest. Then, pulse shaping of the interesting sequences was done, and the autocorrelation functions and power spectra of these shaped sequences were determined.

(2) A digital computer was used to determine the autocorrelation function and power spectra, of "shaped" m-sequences.

(3) Computer results were verified in the laboratory.

Some results of interest include:

(a) The discovery of particular pulse shapes and sequences having spectra with small sidelobe levels.

(b) The realization of relatively simple circuitry to obtain pulses of various shapes.

(c) The implementation of a computer program to generate all binary sequences of any length. This program also calculates the autocorrelation function of each sequence (periodic or aperiodic) and provides a printout of those autocorrelation functions which satisfy predetermined criteria.

(d) The implementation of a computer program to shape sequences, and calculate, print and plot their autocorrelation functions and power spectra.

B. CONTENTS OF THIS REPORT

Chapter II provides the necessary background by defining basic properties of binary sequences, voltage and power spectra, autocorrelation function and m-sequences.

The theory, computer programs and results, and the experimental system and results used to select, generate and shape binary sequences are presented in Chapter III.

Recommendations and conclusions are contained in Chapter IV.

II. BACKGROUND

A. BINARY SEQUENCES

A binary sequence is a list of elements, each of which can have one of two distinct values. These values are usually represented either by +1 and -1, by 1 and 0 or by + and -.

For example, sequence A may be written:

$$A = + + - + \quad \text{or} \quad A = 1\ 1\ 0\ 1 \quad \text{or} \quad A = +1,+1,-1,+1\ .$$

The number of elements in a sequence is the length, denoted here by L. In the above example, the length of the sequence A is L = 4. The number of different possible binary sequences of length L is 2^L.

In electrical engineering, the binary sequence has a voltage equivalent v(t), where, for example, 1 may be represented by a voltage level = +V, and 0 by a voltage level = -V (bipolar logic) where ε is the bit duration, as shown in Fig. 1. (In unipolar logic either 1 or 0 is represented by zero volts or "ground.")

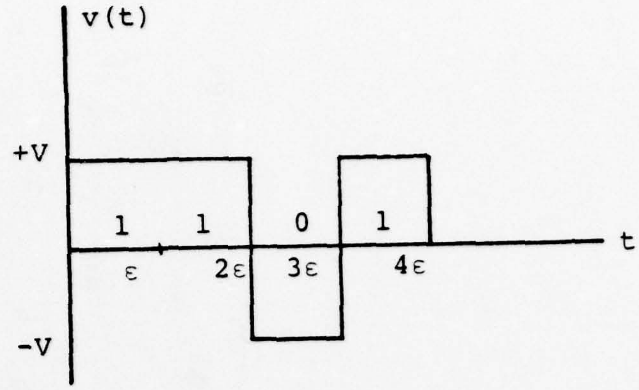


FIGURE 1. VOLTAGE EQUIVALENT OF A BINARY SEQUENCE.

B. THE AMPLITUDE (VOLTAGE) SPECTRUM

Any function v(t) having certain mathematical properties* has a Fourier transform V(f) defined by the expression:

$$V(f) = \int_{-\infty}^{+\infty} v(t)\, e^{-j2\pi ft}\, dt = F[v(t)]$$

where, in this report, v(t) is a function of time and V(f) is a function of frequency, with f having units which are the inverse of t. If t corresponds to seconds, f is in Hertz.

The inverse transform of V(f) is

$$F^{-1}[V(f)] = v(t) = \int_{-\infty}^{+\infty} V(f)\, e^{+j2\pi ft}\, df$$

---

*A function has a Fourier transform if it has a finite number of maxima, minima, discontinuities and integrable infinities, and does not have infinite energy, i.e.

$$\int_{-\infty}^{+\infty} |v(t)|^2\, dt \quad \text{is finite.}$$

In general, the Fourier transform is a complex quantity:

$$V(f) = R(f) + j\,I(f) = |V(f)|e^{j\theta_v(f)}$$

where R(f) is the real part and I(f) is the imaginary part of the Fourier transform.

$|V(f)|$ is called the amplitude spectrum of v(t) and is given by:

$$|V(f)| = \sqrt{R^2(f) + I^2(f)}$$

which describes the amplitude distribution of the signal (voltage) with frequency.

A spectrum analyzer excited by v(t), displays typically, $|V(f)|$, the amplitude spectrum of v(t).

$\theta_v(f)$ is the phase spectrum of v(t) and is given by:

$$\theta_v(f) = \arctan\left[\frac{I(f)}{R(f)}\right]$$

When v(t) is a real signal, then V(f) is defined for all $-\infty \leq f \leq +\infty$, and $|V(f)|$ is an even function, while $\theta_v(f)$ is an odd function.

When v(t) is periodic, then the transform consists of delta functions and the spectrum is discrete [Refs. 1,2,3].

C. POWER SPECTRUM AND AUTOCORRELATION FUNCTION

1. For a signal v(t), which exists for all time, we define the power spectral density function $G_v(f)$ as a real, even, non-negative function of frequency, which gives the total average power P watts per ohm when integrated. That is:

$$P = \int_{-\infty}^{+\infty} G_v(f)\, df = \text{watts}$$

The power spectrum $G_v(f)$ provides a useful frequency description of v(t) even when the equation for v(t) is not known. It is a partial description though, because it gives only the distribution of signal power with frequency; all the phase information is lost.

2. The autocorrelation function $R_{vv}(\tau)$ of a signal v(t) having a power spectrum, is defined as:

$$R_{vv}(\tau) = \overline{v(t)\ v(t-\tau)}$$

$$= \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} v(t)v(t-\tau)dt$$

which is the time average of the product of the signal and itself delayed by τ sec.

If v(t) is periodic with period T, the integrand above is periodic, and the time average can be taken over a single period:

$$R_{VV}(\tau) = \frac{1}{T} \int_0^T v(t)\, v(t-\tau)\, dt$$

$R_{VV}(\tau)$ gives a measure of the similarity between the signal at time t and at time τ seconds earlier or later. The degree of similarity depends on τ.

The autocorrelation function $R_{VV}(\tau)$ and the power spectrum $G_V(f)$ of a signal v(t) are a Fourier transform pair; that is,

$$R_{VV}(\tau) \Longleftrightarrow G_V(f)$$

Consequently, $R_{VV}(\tau)$ may be known or found even when the equation for v(t) is not known. Then, taking the Fourier transform of $R_{VV}(\tau)$, gives the power spectrum $G_V(f)$ of v(t).

When v(t) consists of samples of a continuous signal, then the autocorrelation function is obtained as a sum involving these sample values [Refs. 1-2].

D. MAXIMAL LENGTH SEQUENCES

1. Definition and Generation

Maximal length sequences (m-sequences) are defined as the longest codes that can be generated by a given shift-register or a delay element of a given length.

They are typically generated by modulo-two addition from selected outputs of a shift-register as shown in Fig. 2a.

The sequence length is $L = 2^n-1$ bits, where n is the number of stages in the shift register [Refs. 4 and 5].

In this work, the autocorrelation function and the power spectra of these m-sequences are of interest.

2. Autocorrelation Function (ACF) of m-sequences

A plot of the ACF of m-sequences is shown in Fig. 2, for the case where $v(t)$ has value $\pm V$. In this figure the m-sequence is generated by a shift-register of 4 stages with a corresponding sequence length of $L = 2^4-1 = 15$. The duration of each pulse or bit is denoted by ε and thus, the bit rate is $1/\varepsilon$ bits per second.

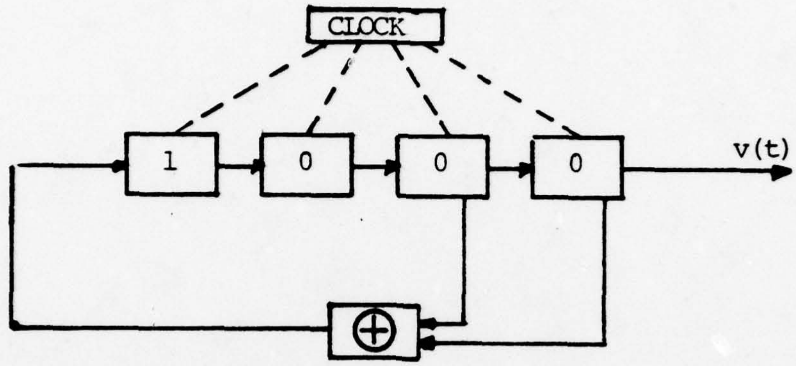
For $\varepsilon = 1$ the value of this plot for zero displacement or "slide" ($\tau = 0$) is equal to LV^2 and decreases linearly to a minimum constant value of $-1/V^2$, when the displacement is greater than one bit.

The shape of the ACF of Fig. 2 is useful in applications requiring detection of a signal (binary sequence) in the presence of noise. The large main lobe at $\tau = 0$ and $\tau = kT$ (k is an integer and T is the period of the sequence) permits signal recognition by correlating receivers. The absence of side lobes reduces the risk of false alarms.

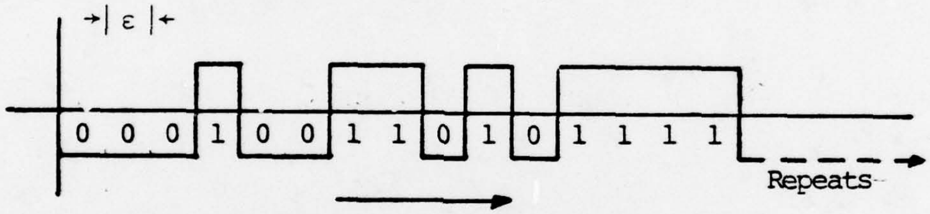
Consequently, m-sequences are used in a variety of applications including radar, sonar and spread spectrum digital communications systems.

3. Power Spectrum

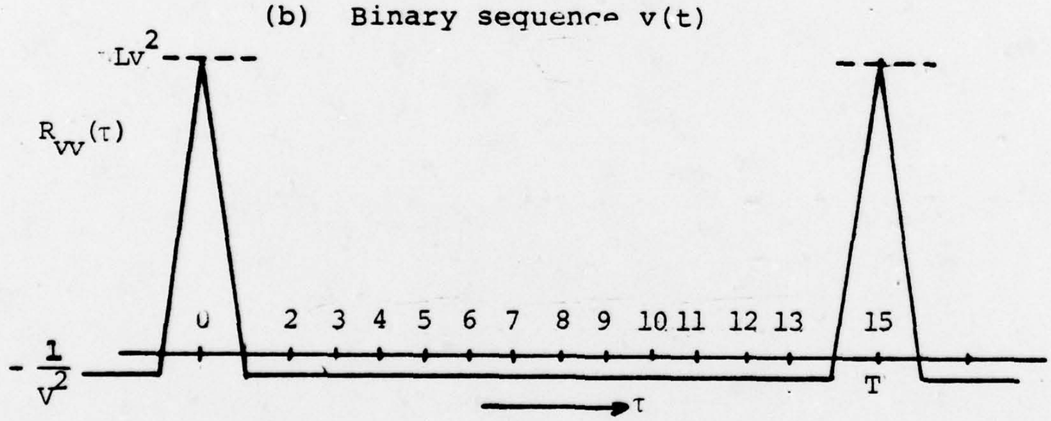
The power spectrum of an m-sequence is obtained by taking the Fourier transform of its autocorrelation function.



(a) Feedback shift register



(b) Binary sequence v(t)



(c) ACF of binary sequence

Fig. 2. GENERATION OF A 15-BIT m-SEQUENCE AND ITS AUTOCORRELATION FUNCTION

Because of the fixed triangular form of the ACF of all m-sequences, the $(\frac{\sin x}{x})^2$ spectrum shape is a property of all m-sequences independent of their length L.

As shown in Fig. 3, the power spectrum of these periodic m-sequences consists of discrete spectral lines within the envelope E, where:

$$E = [\frac{\sin(\pi fT)}{\pi fT}]^2$$

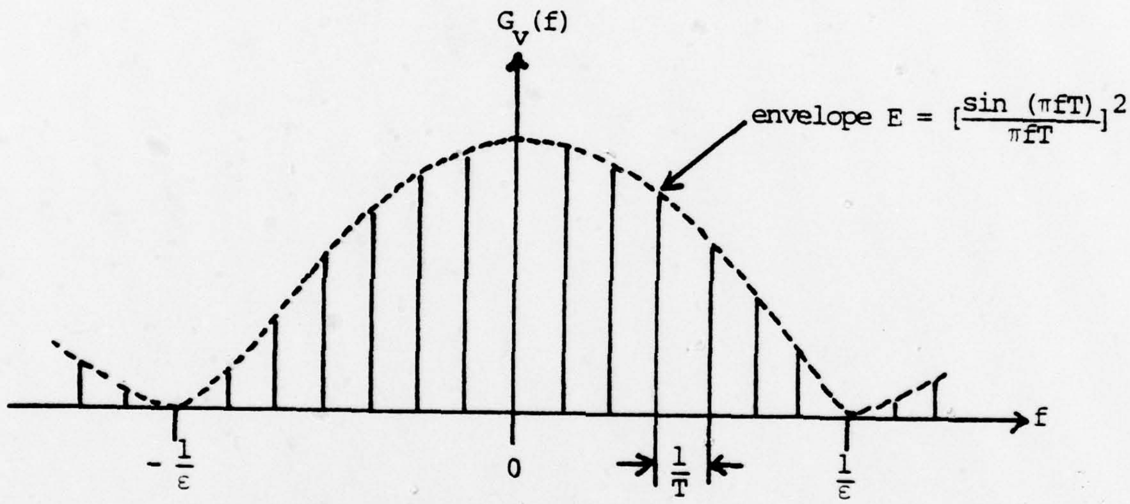


Figure 3. POWER SPECTRUM OF AN m-SEQUENCE

The zero crossings or nulls of the envelope, are defined by the bit interval ε. (In spread-spectrum applications, ε is called the "chip" interval.)

Usually, the value of the first zero of the envelope E of the spectrum is called the bandwidth B of the m-sequence. From Fig. 3, $B = \frac{1}{\varepsilon}$. Consequently, as the sequence chip duration ε is decreased (clock or chip rate increased), the bandwidth is increased [Ref. 4].

4. Use in Spread-Spectrum Systems

These unique properties of the m-sequences (ACF and Spectra) are used in Spread-Spectrum systems. In the transmitter, a particular m-sequence is used for one binary data bit, and its complement or another m-sequence is used for the other binary data bit. This technique, allows the spreading of the information spectrum, resulting in jam-resistance and low-probability of intercept communications. Sequence detection and recognition in the receiver is accomplished by using matched filters or correlators, having as an output the ACF of the sequence [Ref. 4].

In this research, we examine methods based on m-sequence pulse shaping which can change the power spectrum to some desired form. The nulls of the $(\frac{\sin x}{x})^2$ spectrum are related to the sequence clock frequency, which provides casual observers information on the signal format. Of interest then, is investigation of pulse shapes which either eliminate or relocate the nulls in the spectrum of the shaped sequences.

Of course, the original pulses can be shaped unpredictably by filtering with a resulting change in the form of the ACF (and spectra) which is used for signal detection. In this work, we generate pulses having a desired particular shape before transmission. We investigate here the properties (spectra and ACF) of these pulses of known shape.

III. SHAPING BINARY SEQUENCES

A. DEFINITION AND EXAMPLES

By "shaping" a binary sequence v(t) consisting of rectangular pulses, we mean the substitution or change of the sequence's original pulses with elements of different shape and energy but of the same peak amplitude and width.

Thus, a "shaped" sequence will maintain its original list of elements with peak amplitudes having the same two distinct values but not piece-wise constant (not rectangular pulses).

As an example, consider the sequence A = 1 1 0 1 represented by rectangular pulses and then "shaped" using triangular pulses as shown in Fig. 4.

B. THEORY

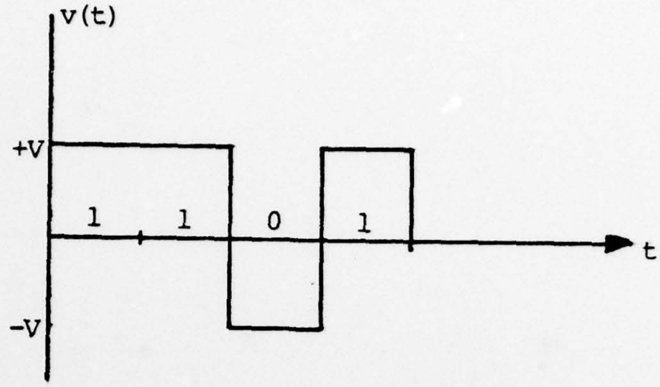
1. The ACF of Rectangular Pulse Sequences

As shown in Chapter II, Section C.2, the ACF of a periodic, two-level voltage v(t) is defined as the integral:

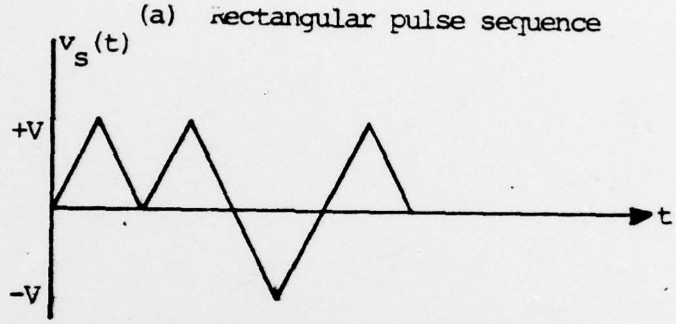
$$R_{vv}(\tau) = \frac{1}{T}\int_0^T v(t)v(t-\tau)dt = \frac{1}{\eta\varepsilon}\int_0^{\eta\varepsilon} v(t)v(t-\tau)dt$$

where η is the number of pulses in one period of the sequence and ε is the pulse duration.

The way to find the ACF $R_{vv}(\tau)$ of a digital sequence v(t) is to "slide" the sequence past itself to the right or



(a) rectangular pulse sequence



(b) Triangular pulse sequence

Fig. 4. A BINARY SEQUENCE, BEFORE AND AFTER SHAPING WITH TRIANGULAR WAVEFORM

left and at each position to form the product of the corresponding pulses or elements of the sequence with its shifted replica. Then, the area of the product waveform is found, and this corresponds to the ACF of the sequence at this position.

It can be seen from the equation for $R_{vv}(\tau)$ and from the above procedure, that when v(t) is a piecewise constant

function, $R_{VV}(\tau)$ will be piecewise linear. The linear segments terminate at multiples of ε, the duration of one bit. In Appendix A, a simple method of obtaining the periodic ACF is presented.

2. <u>The ACF of the Triangular Pulse Sequence</u>

We present now the computer calculation of the ACF of one triangular pulse (for simplicity). In Appendix A we show that the ACF of a sequence of such pulses (bits) can be obtained by the addition of the results for one pulse. Fig. 5 is the resulting computer plot where the peak amplitude is 10.0 and 20 sample points were used in the calculation.

From the above result we conclude that the ACF of a triangular pulse sequence is not piecewise linear anymore. Consequently the spectrum of a triangular "shaped" pulse sequence, does not have the $(\frac{\sin x}{x})^2$ form. In general, the spectrum of any non-rectangular shaped pulse sequence does not have the $(\frac{\sin x}{x})^2$ form. Based on this conclusion, three basic and known waveforms are initially chosen for "shaping":

(a) Triangular

(b) Raised sine

(c) Gaussian

C. COMPUTER SHAPING AND RESULTS

1. <u>ACF and Spectra of Shaped m-sequences</u>

Appendix B contains the computer program by which an m-sequence is extended and shaped (if so desired) and its ACF and spectra calculated and plotted.

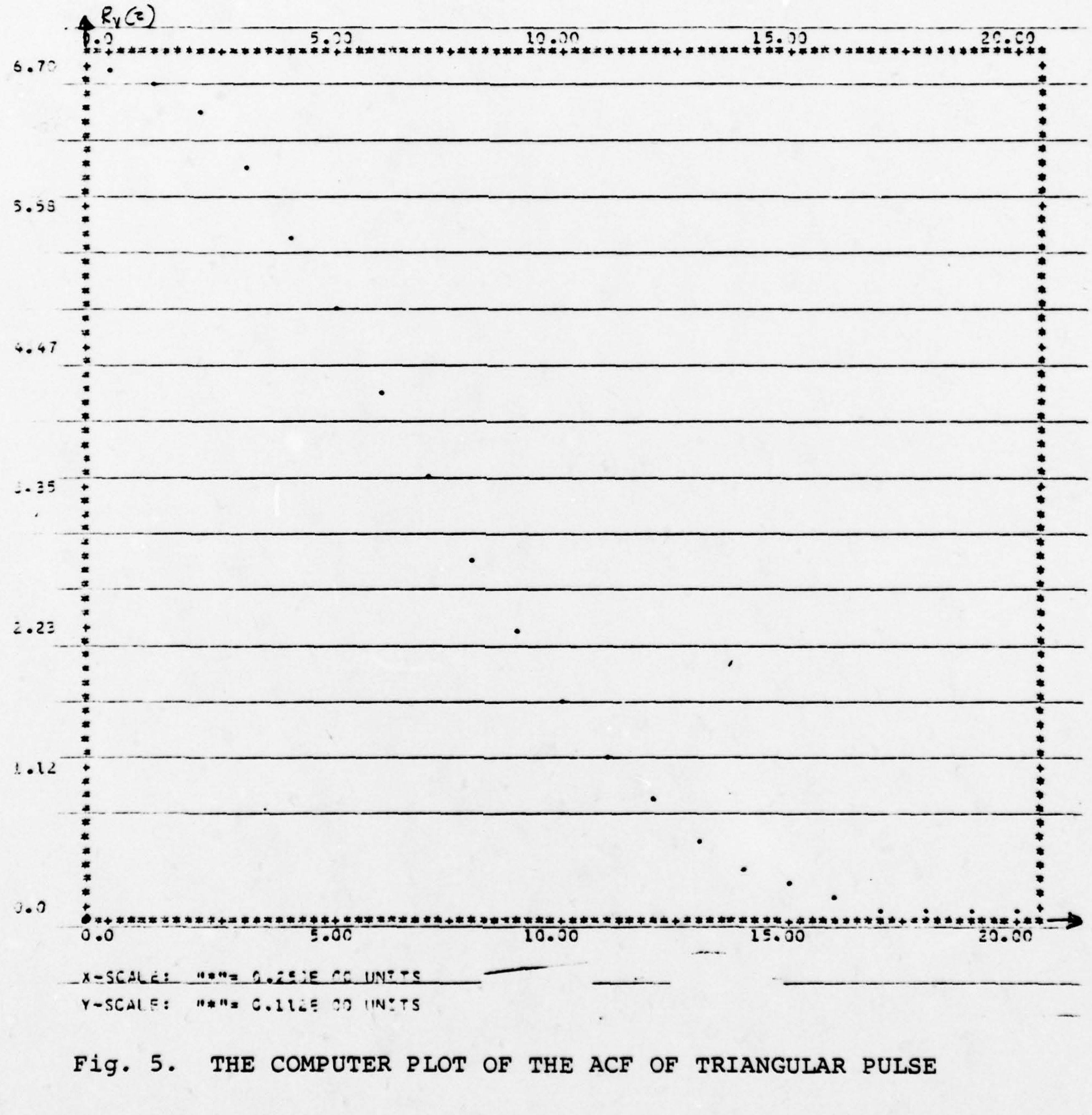


Fig. 5. THE COMPUTER PLOT OF THE ACF OF TRIANGULAR PULSE

Figs. 6 through 8 represent some of the computer results of interest. Additional results and printouts are presented in Appendix B.

From these figures we have the first encouraging indications of the shaping effect, particularly from the raised sine and triangle (the Gaussian shape didn't give results of comparable interest).

We observe that the autocorrelation functions retain their usable form by having a single definite maximum value and small sidelobe levels. The power spectra show a high energy concentration in the low frequencies with a corresponding bandwidth increase and also a considerable decrease of the sidelobe levels.

In the following computer plots some results of interest are shown. Fig. 6a is a 7-bit m-sequence (rectangular). Figs. 6b and 6c show the ACF and power spectrum, respectively, of the 7-bit m-sequence of Fig. 6a. Fig. 7 shows the results when the m-sequence of Fig. 6 has the raised since shape. Fig. 8 shows the results when the m-sequence of Fig. 6 has the raised triangle shape.

2. <u>Investigation of Interesting Arbitrary Sequences</u>

This computer search is motivated by the fact that except for a few categories of sequences (i.e., m-sequences) with interesting properties for specific applications, very little is known of the properties of arbitrary sequences. It is desirable to find sequences having spectra which will differ significantly from the $(\frac{\sin x}{x})^2$ form. In the absence

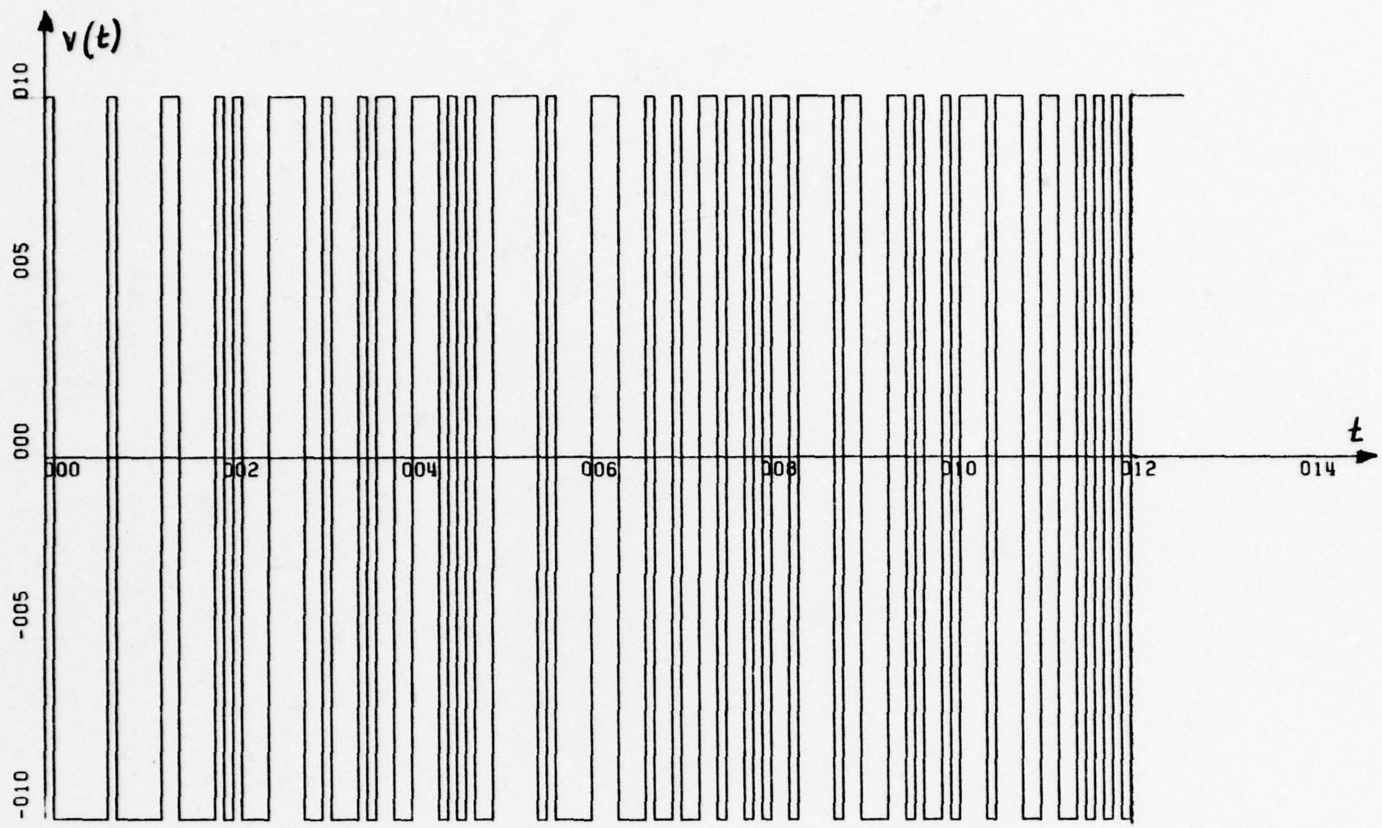


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Fig. 6a. THE RECTANGULAR SHAPE 127-BIT m-SEQUENCE.

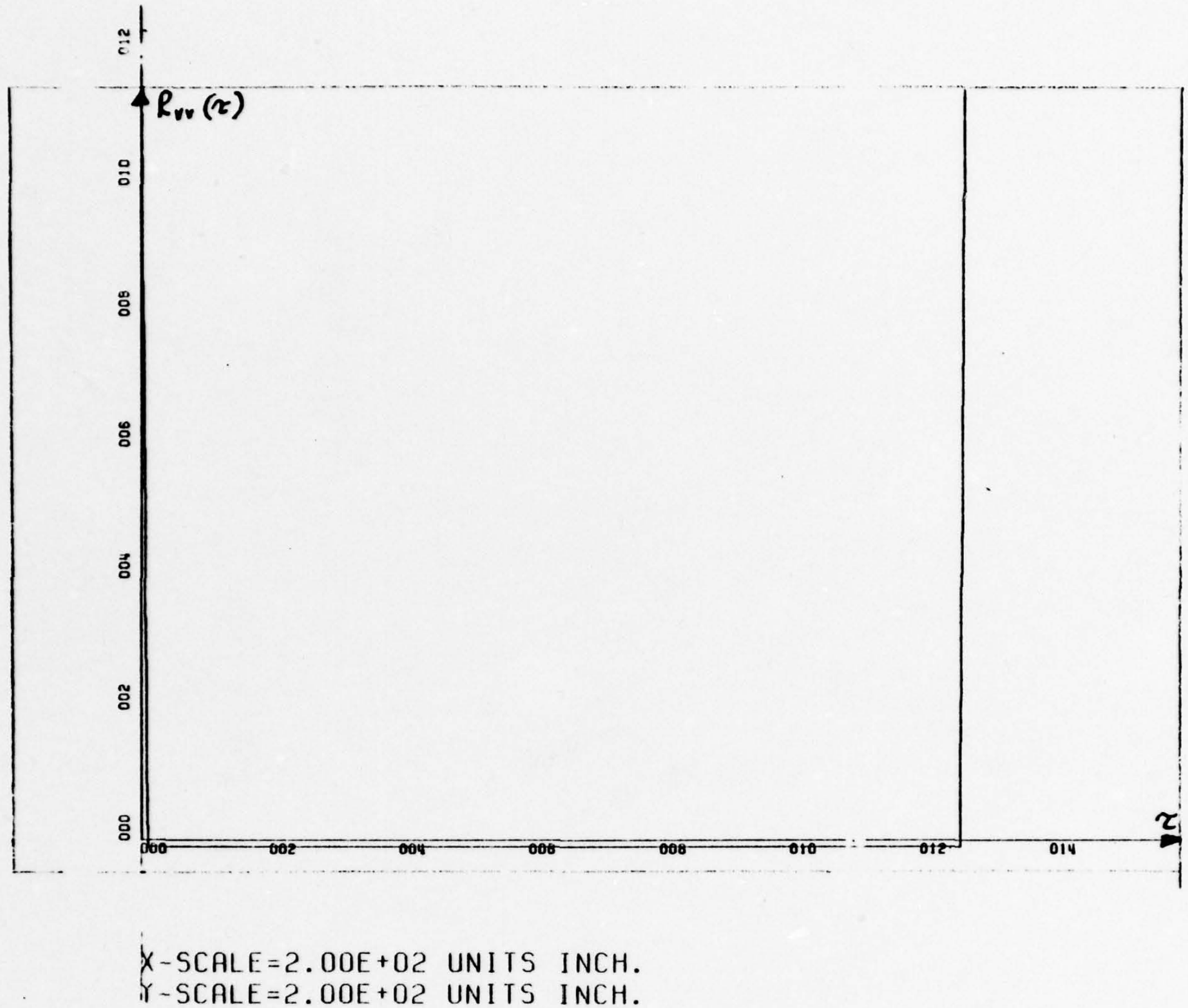

Fig. 6b. THE ACF OF THE RECTANGULAR SHAPE 127-BIT m-SEQUENCE.

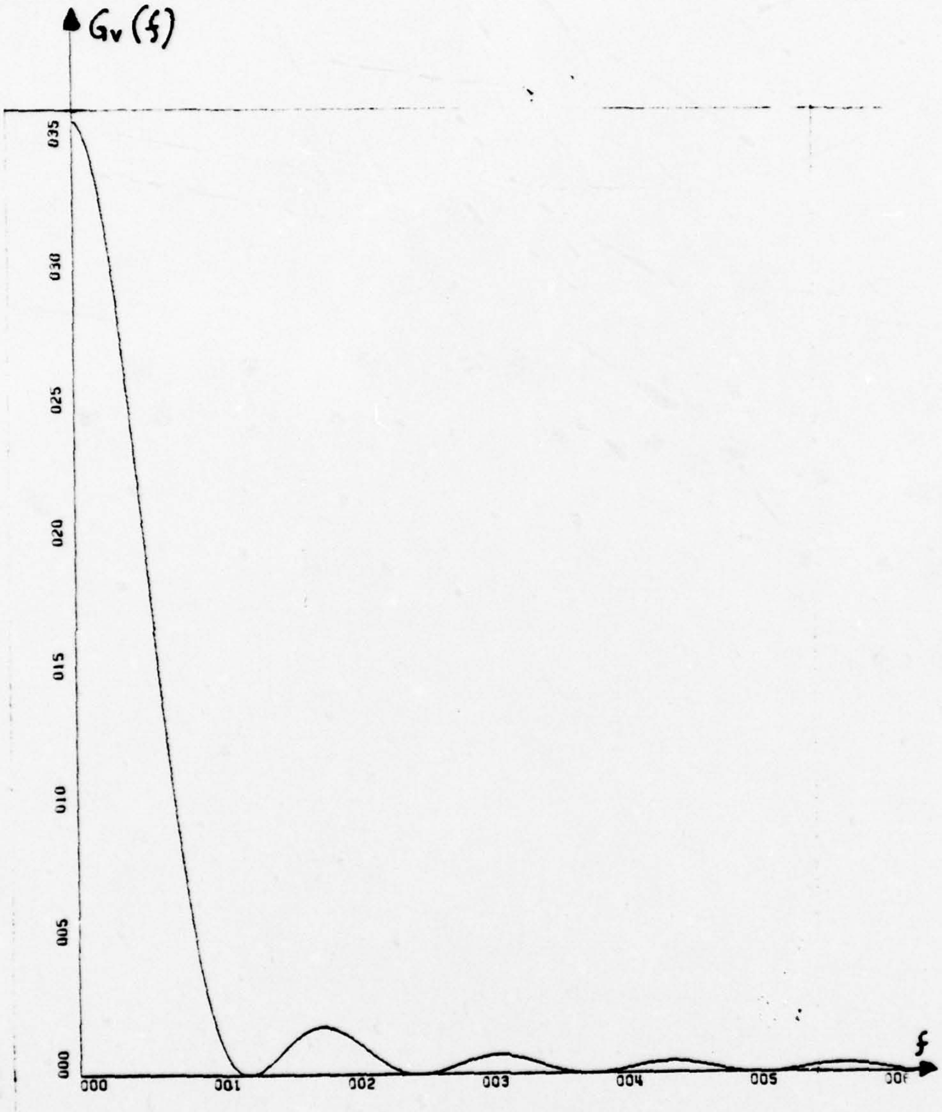

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Fig. 6c. THE POWER SPECTRUM (LINEAR) OF THE RECTANGULAR SHAPE 127-BIT m-SEQUENCE.

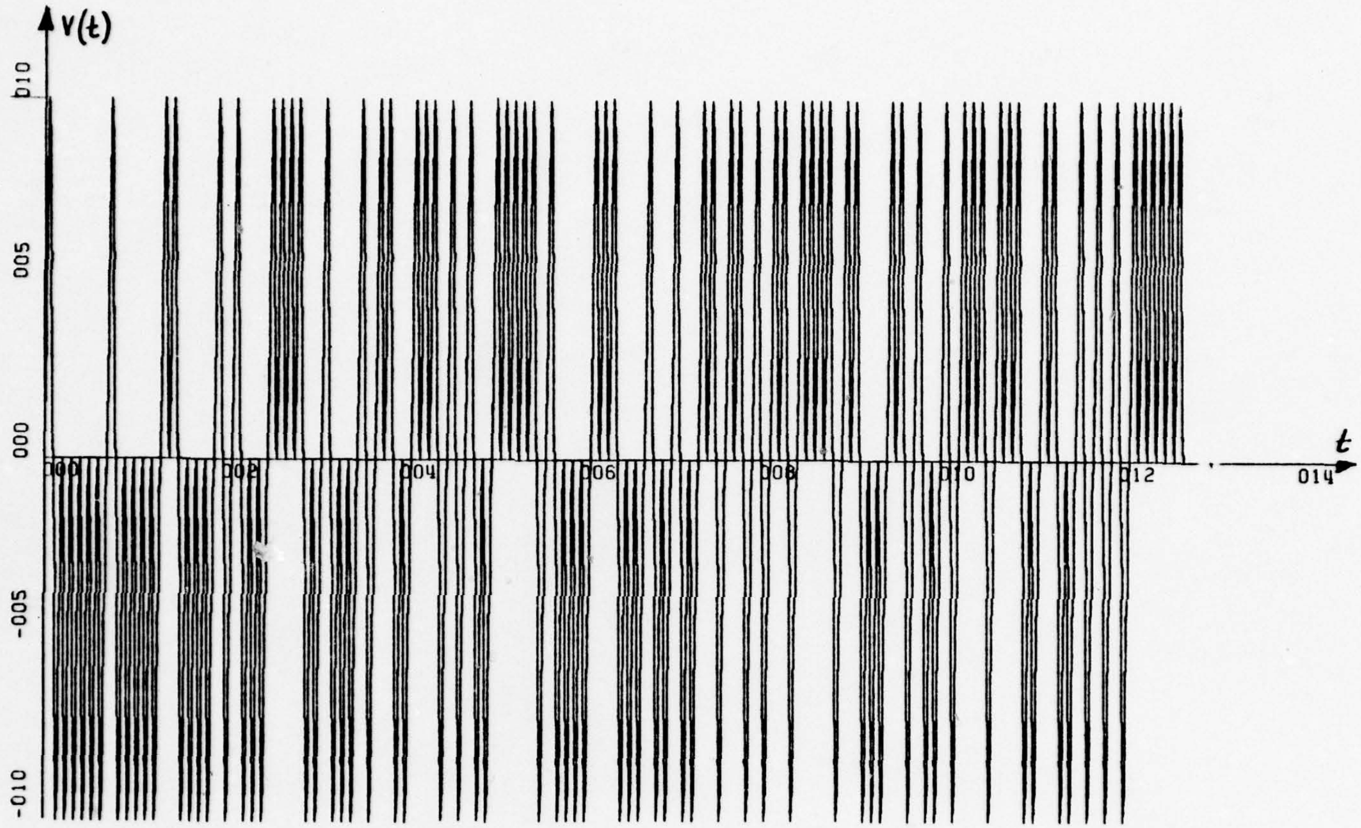

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Fig. 7a. THE RAISED SINE SHAPE 127-BIT m-SEQUENCE.

X-SCALE=2.00E+02 UNITS INCH.
Y-SCALE=1.00E+02 UNITS INCH.

Fig. 7b. THE ACF OF THE RAISED SINE SHAPE 127-BIT m-SEQUENCE.

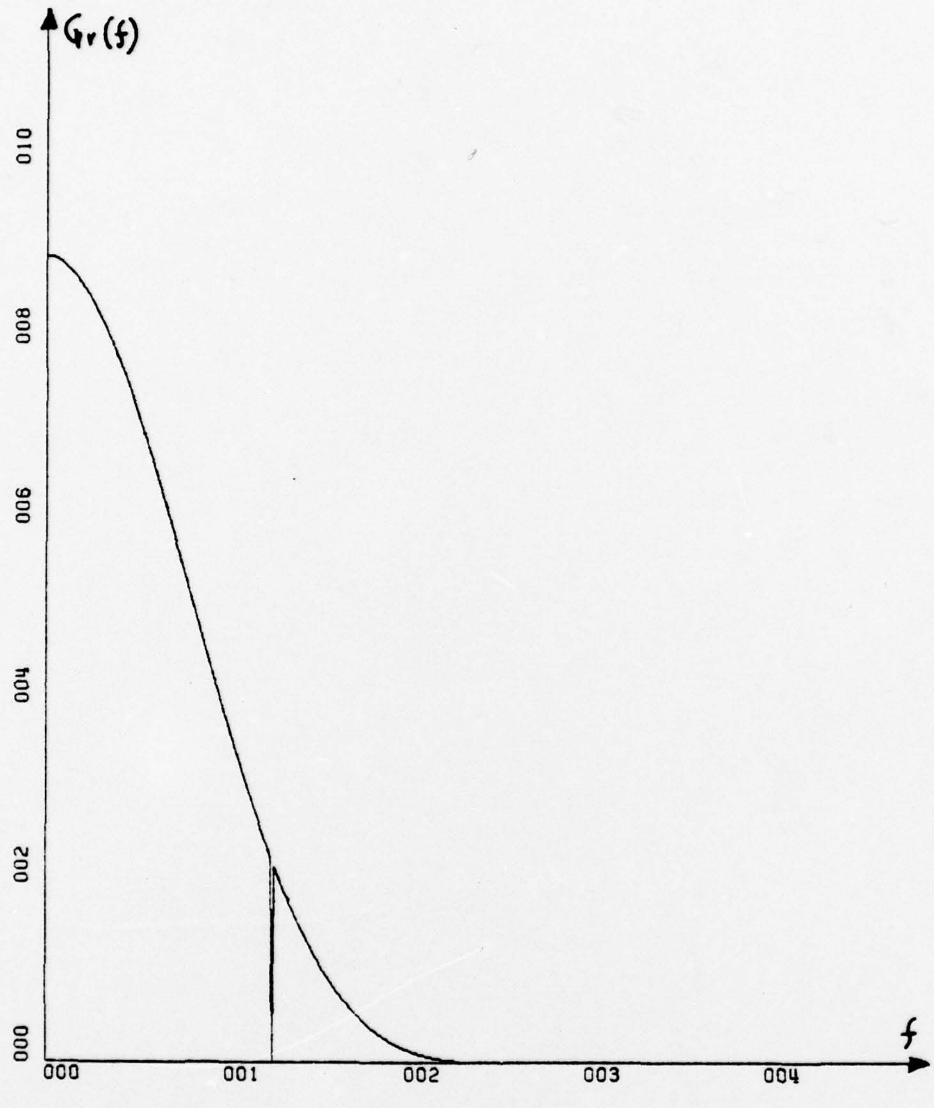

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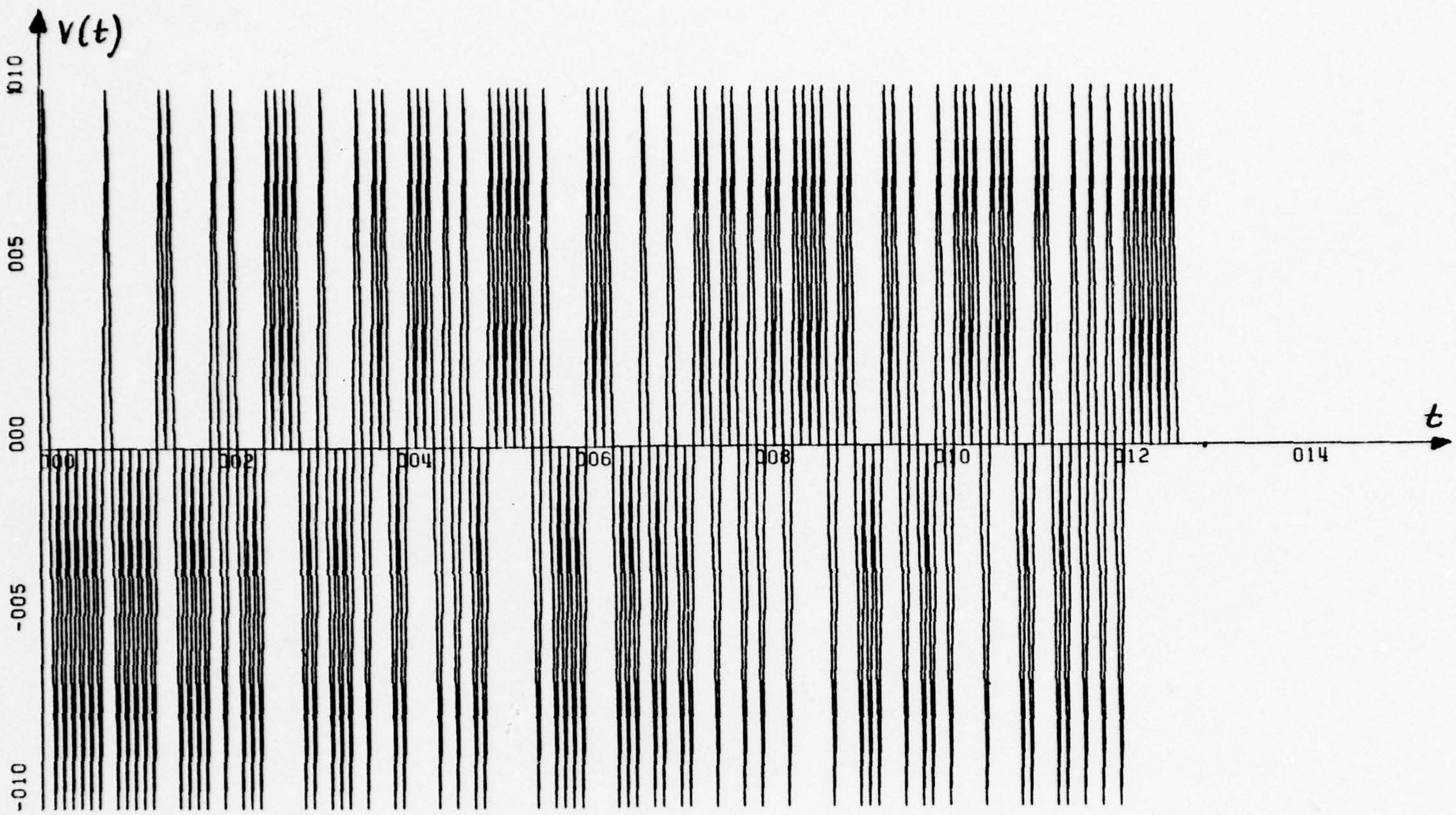
Fig. 7c. THE POWER SPECTRUM OF THE RAISED SINE SHAPE 127-BIT m-SEQUENCE.

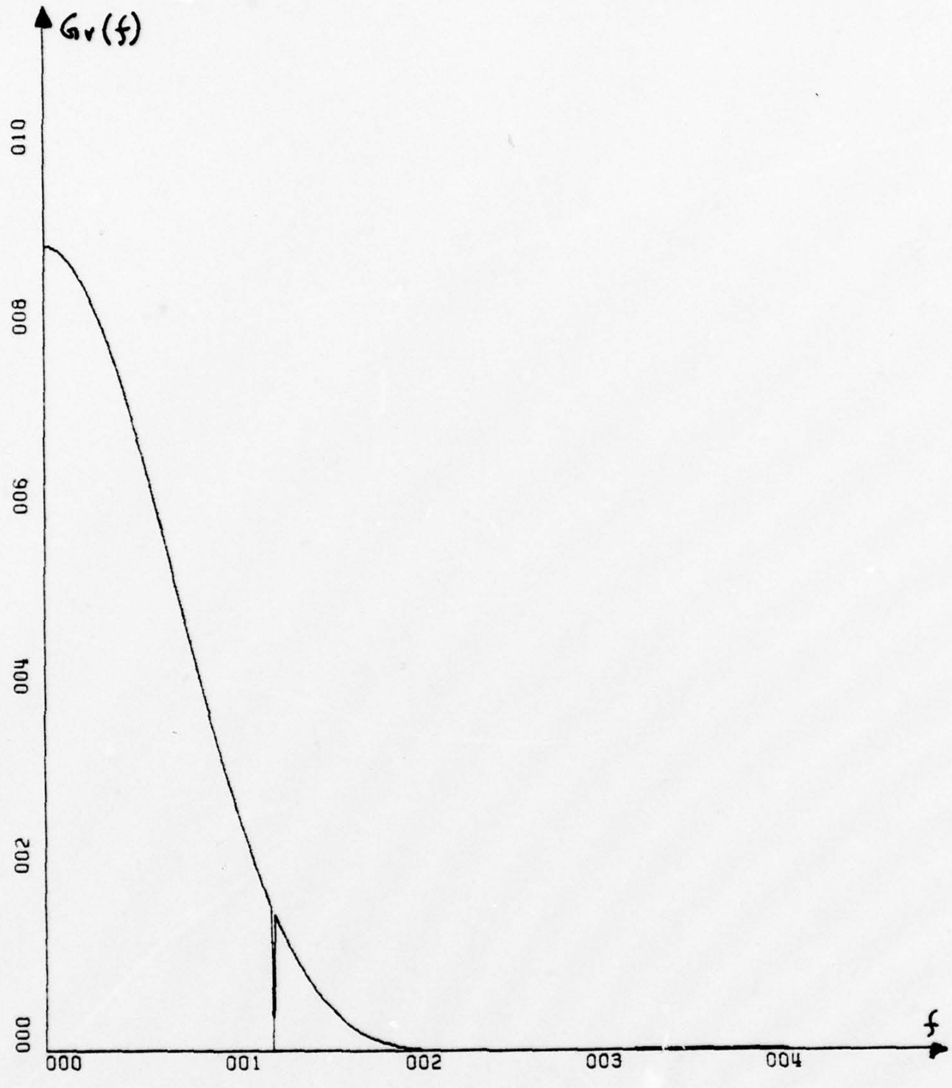


X-SCALE=2.00E+02 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.

Fig. 8a. THE TRIANGLE SHAPE 127-BIT m-SEQUENCE.

X-SCALE=2.00E+02 UNITS INCH.
Y-SCALE=1.00E+02 UNITS INCH.

Fig. 8b. THE ACF OF THE TRIANGULAR SHAPE 127-BIT m-SEQUENCE.



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Y-SCALE=2.00E+01 UNITS INCH.

Fig. 8c. THE POWER SPECTRUM (LINEAR) OF THE TRIANGULAR SHAPE 127-BIT m-SEQUENCE.

of theory, we proceed to generate as many sequences as possible, to examine their ACF and spectra, and then to choose the interesting sequences for further shaping and study.

Because of the large number (2^L) of different sequences of length L, for even modest values of L it is necessary to use a digital computer to search. Since the complement of a sequence has the same ACF as the sequence and since half of all possible sequences of fixed length are complements, we calculate the ACF of only half of the possible different sequences of length L. Even then, an extended search for the $2^{(L-1)}$ sequences of length L is finally limited to L = 20 due to computer time restrictions (30 minutes) using the available IBM-360 computer.

Since the spectrum of interest is (ideally) the rectangular one (uniform) the corresponding ACF will have a $(\frac{\sin x}{x})$ form. Thus, to save time, we use the Fourier transform pair shown in Fig. 9.

So, the search is directed towards finding sequences having periodic ACF like the $(\frac{\sin x}{x})$ form.

Consequently, a computer program is implemented by which half of all sequences of every length are generated, their periodic ACF calculated, and sufficient criteria are

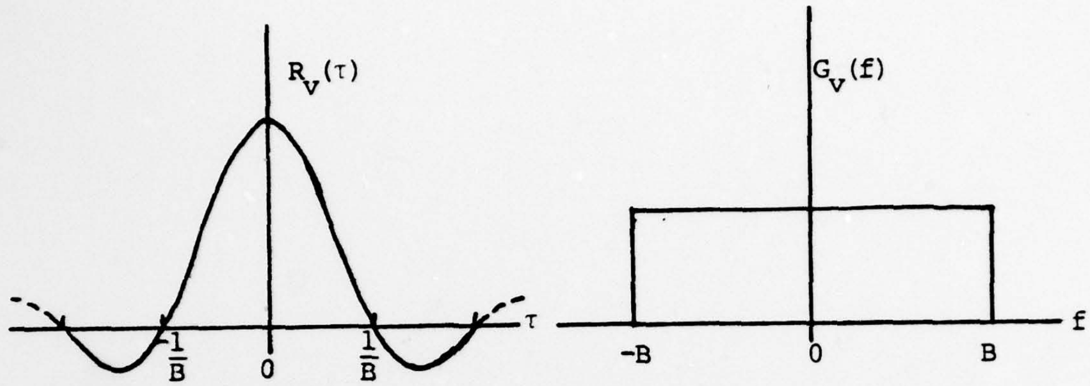


Fig. 9 THE FOURIER TRANSFORM PAIR OF A UNIFORM SPECTRUM

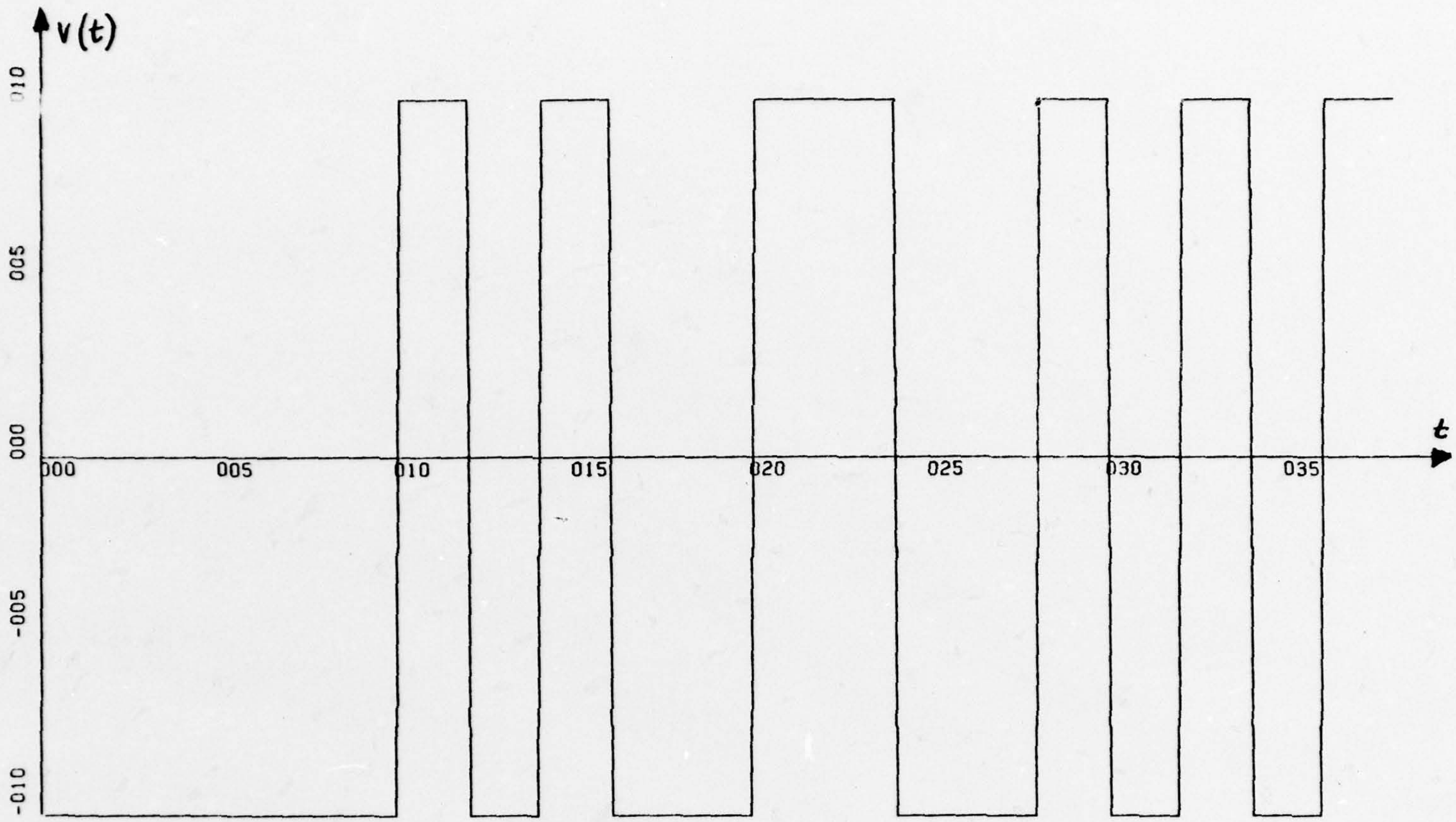
provided for the selection and printout of those sequences having ACF resembling the $\frac{\sin x}{x}$ function. From the resulting printout, interesting sequences are shaped and their ACF and spectra examined. This program is presented in Appendix B along with some of the resulting printouts and plots of selected sequences.

Figures 10 through 12 show some of the results of interest, which correspond to one of the selected sequences of length 19, namely: A = -1,-1,-1,-1,-1,1,-1,1,-1,-1,
1,1,-1,-1,1,-1,1,-1,1

Table 1 contains some of the sequences having properties of interest.

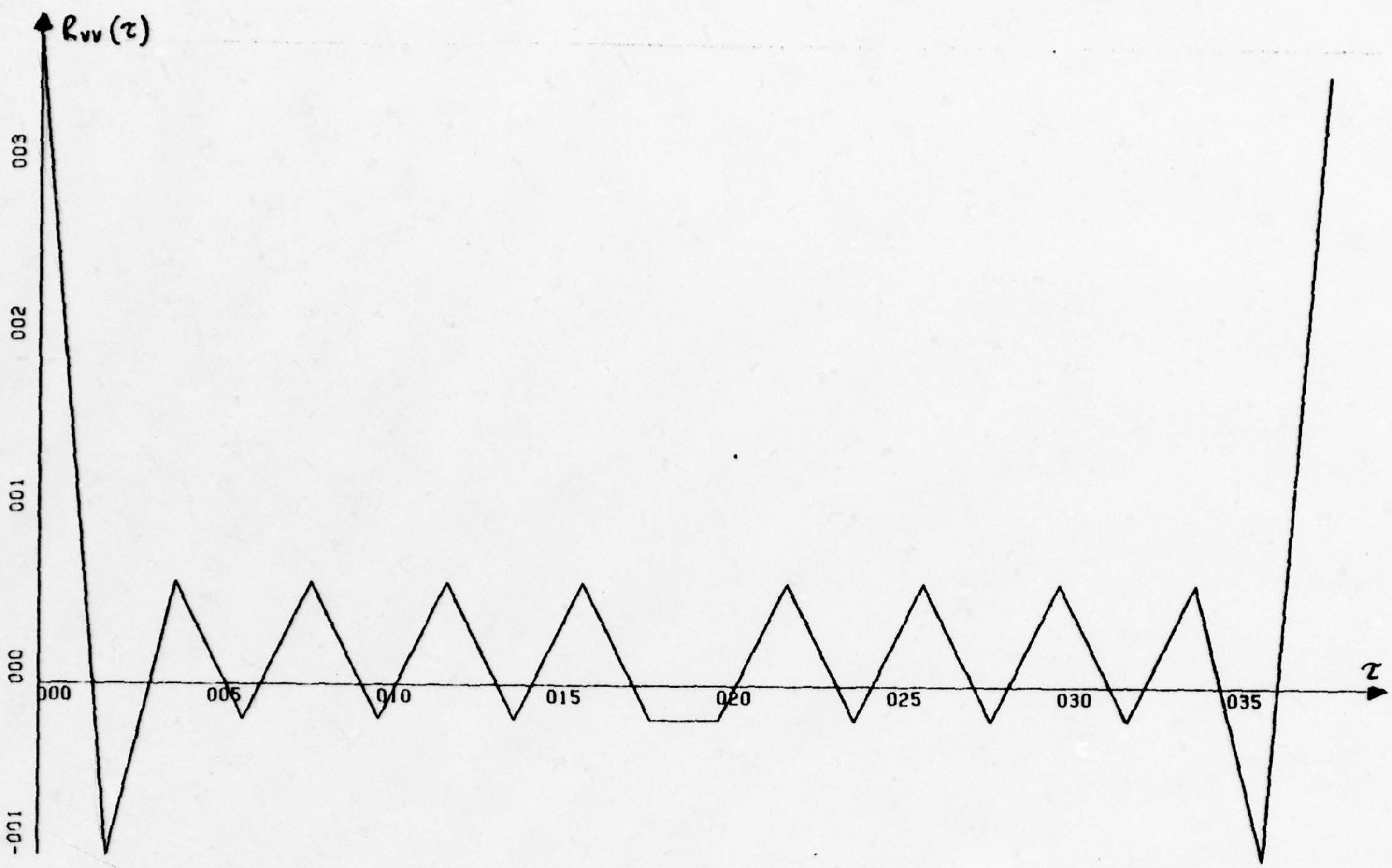
3. <u>Extending the Length of a Sequence</u>

To overcome the computer time limitation, the subroutine EXTEND was constructed to generate and examine longer



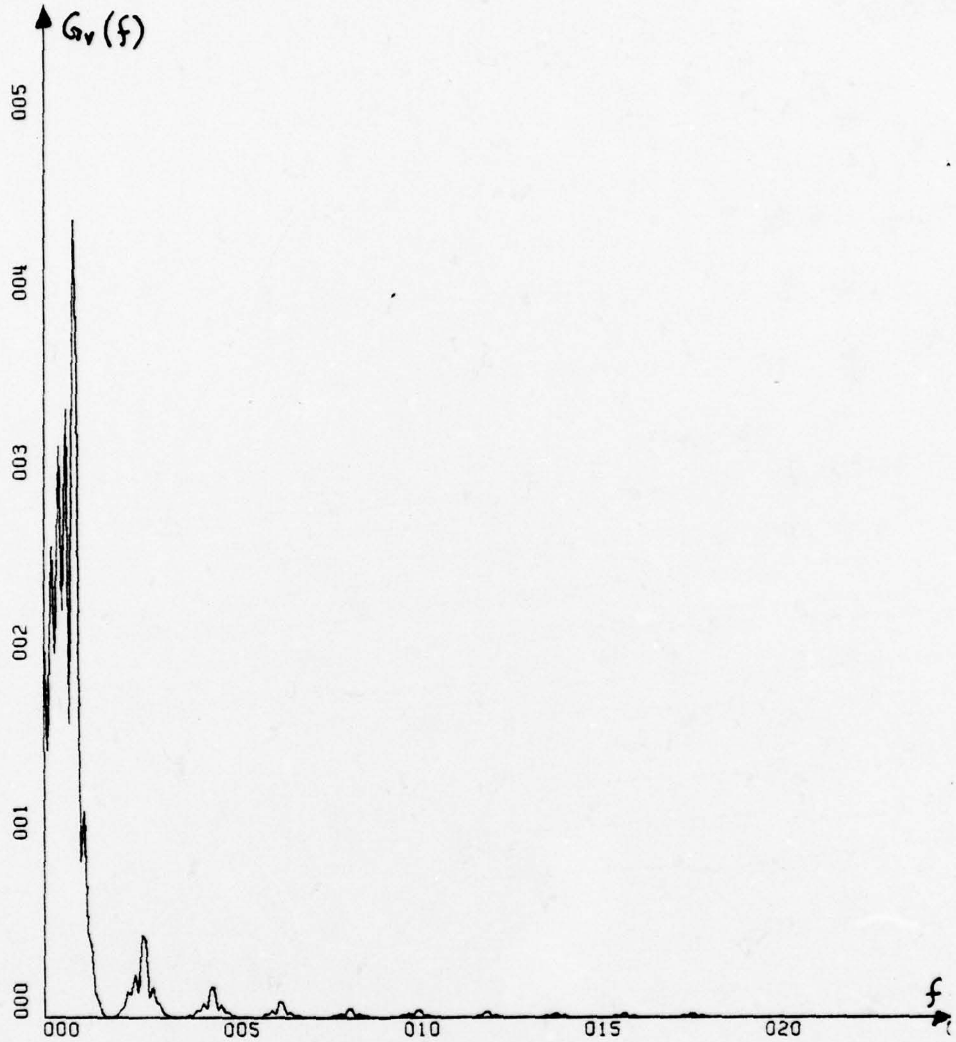
X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.

Fig. 10a. THE RECTANGULAR SHAPE 19-BIT SEQUENCE.



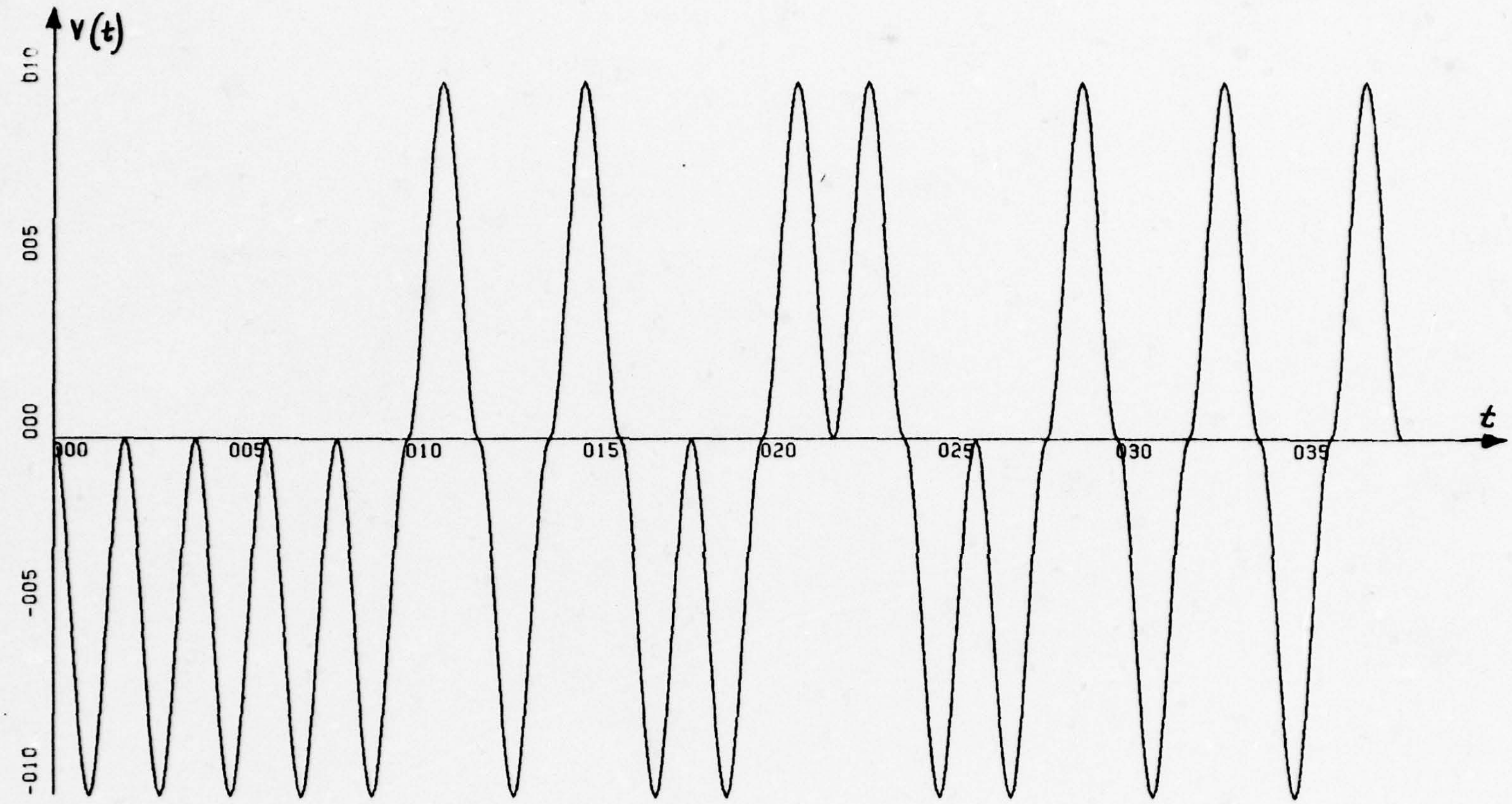
X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=1.00E+02 UNITS INCH.

Fig. 10b. THE ACF OF THE RECTANGULAR SHAPE 19-BIT SEQUENCE.



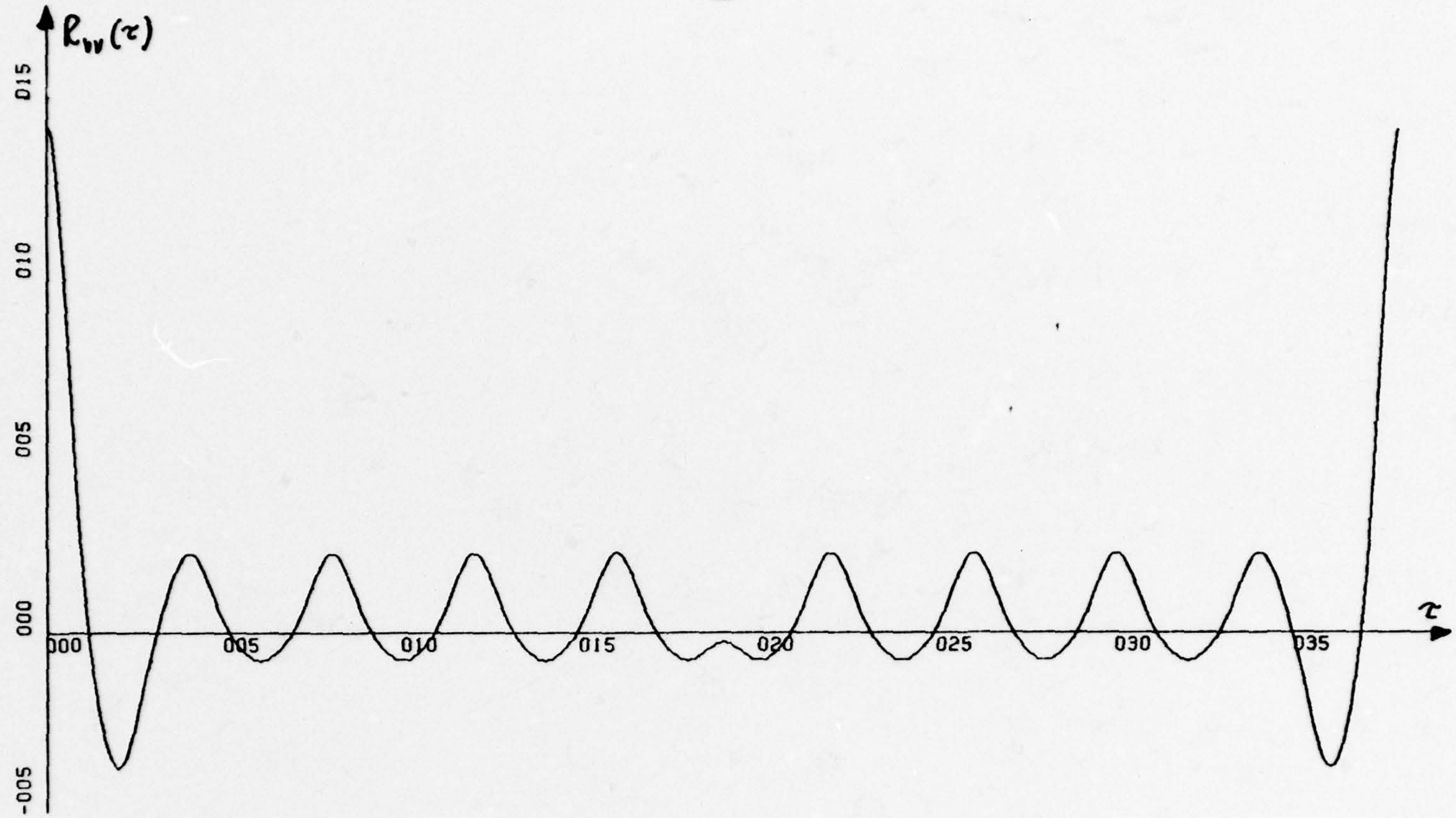
X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=1.00E+02 UNITS INCH.

Fig. 10c. THE POWER SPECTRUM OF THE RECTANGULAR SHAPE 19-BIT SEQUENCE.



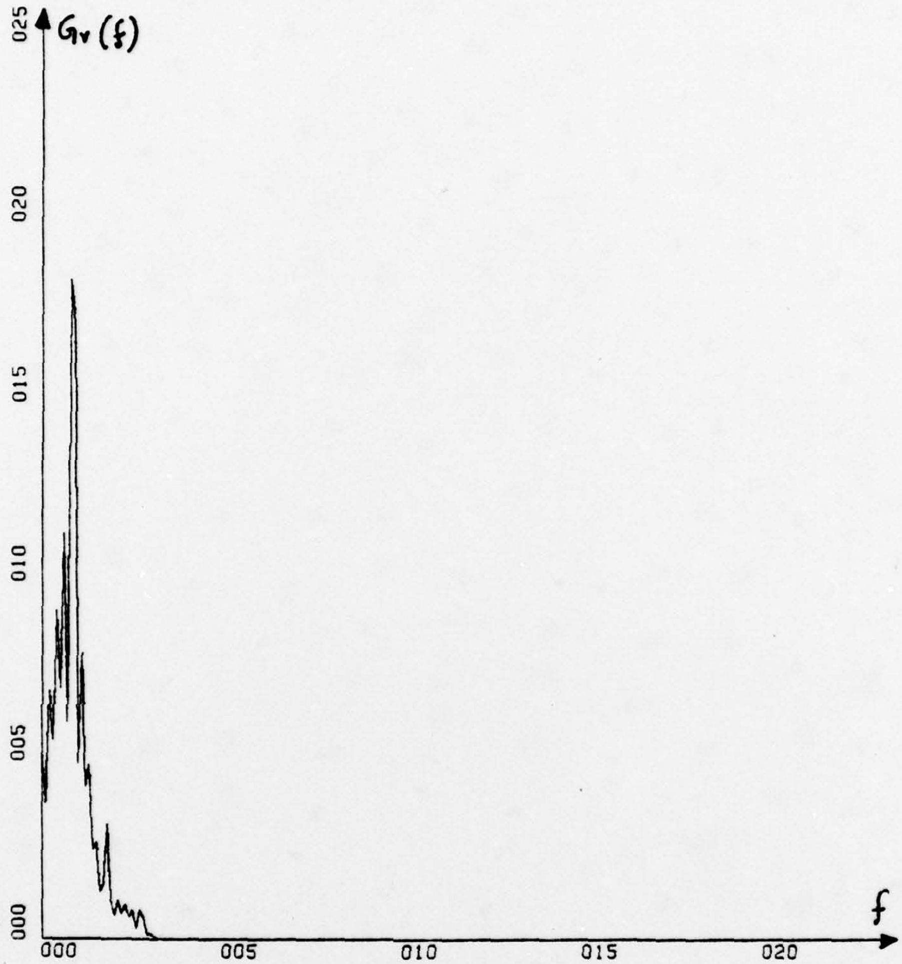
X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.

Fig. 11a. THE RAISED SINE SHAPE 19-BIT SEQUENCE.



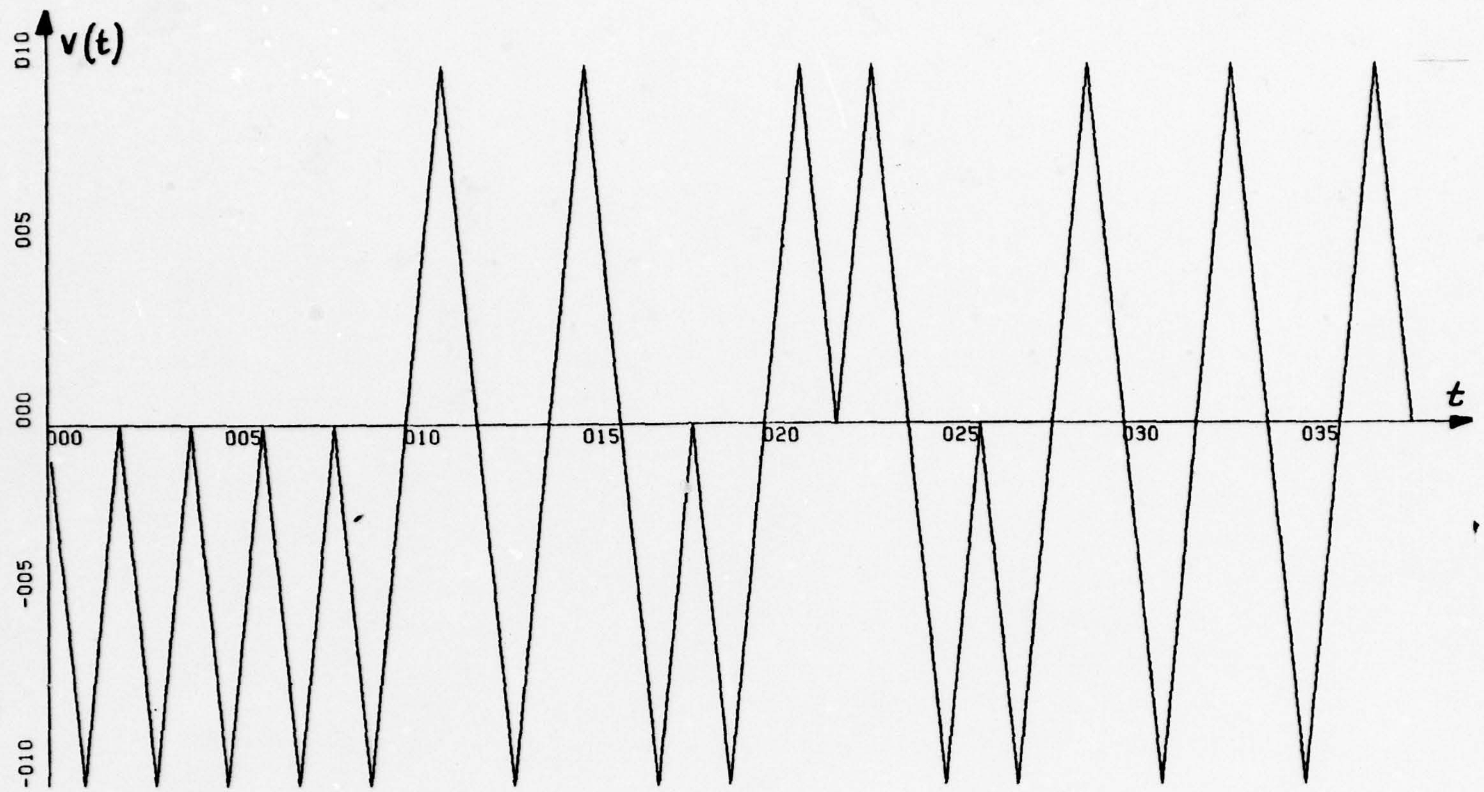
X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E+01 UNITS INCH.

Fig. 11b. THE ACF OF THE RAISED SINE SHAPE 19-BIT SEQUENCE.



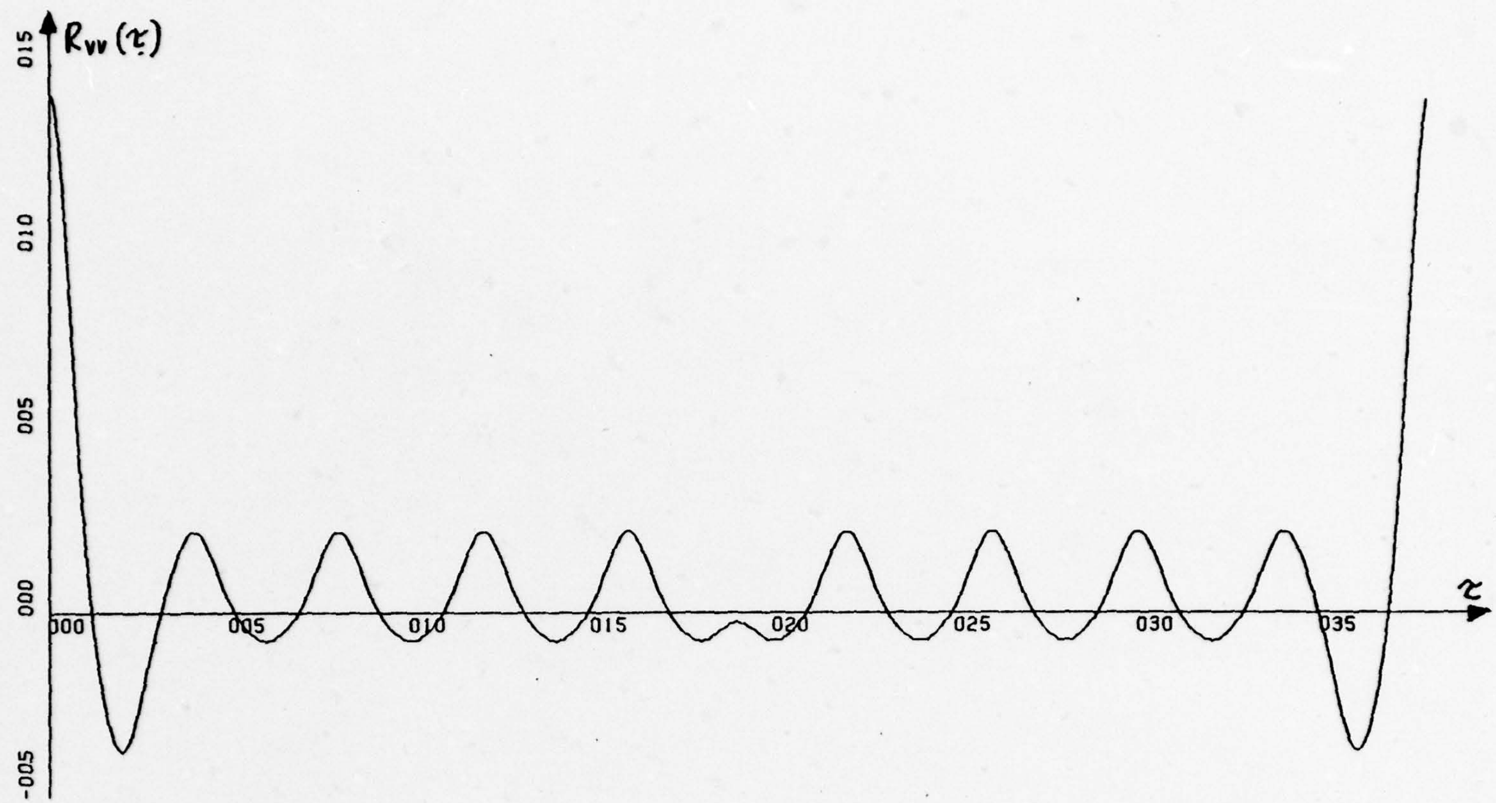
X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E+01 UNITS INCH.

Fig. 11c. THE POWER SPECTRUM OF THE RAISED SINE SHAPE 19-BIT SEQUENCE.



X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.

Fig. 12a. THE TRIANGULAR SHAPE 19-BIT SEQUENCE.



X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E+01 UNITS INCH.

Fig. 12b. THE ACF OF THE TRIANGULAR SHAPE 19-BIT SEQUENCE.

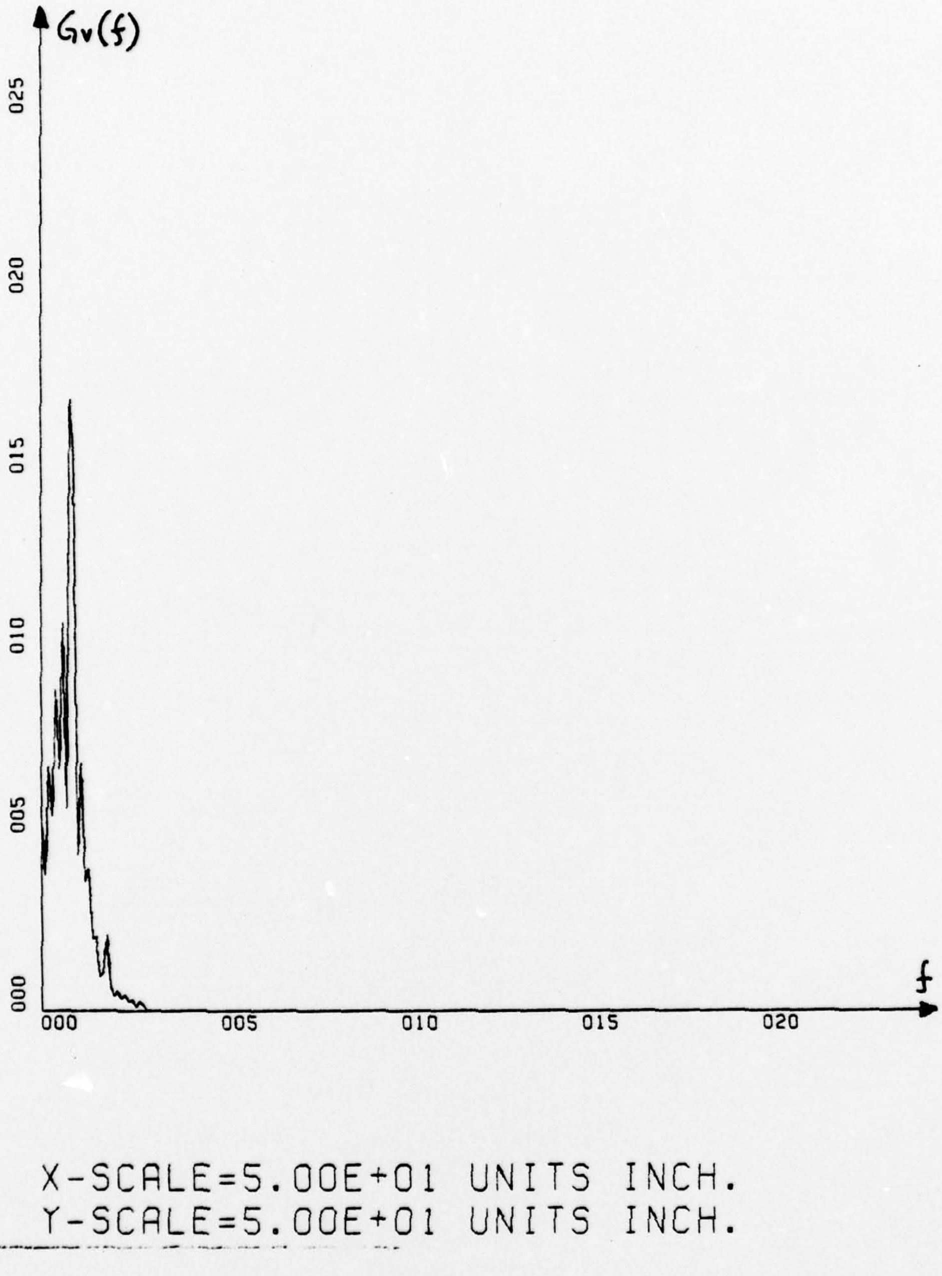


Fig. 12c. THE POWER SPECTRUM OF THE TRIANGULAR SHAPE 19-BIT SEQUENCE.

TABLE I

REMARKS ON SELECTED CODES

a. Elimination of Zero Crossings

Length 11

-1, -1, -1, 1, -1, -1, 1, -1, 1, -1, 1

Length 12, Triangular Shape

-1, -1, -1, -1, 1, -1, 1, -1, 1, -1, 1, 1

Length 15, Triangular Shape

-1, -1, -1, -1, 1, -1, 1, -1, 1, -1, 1, -1, -1, 1, 1

Length 17, Raised Sine Shape

-1, -1, -1, -1, 1, -1, -1, 1, 1, -1, 1, -1, 1, -1, 1, -1, 1

Length 19, Triangular Shape

-1, -1, -1, -1, 1, -1, 1, -1, 1, -1, 1, -1, 1, -1, -1,
1, 1, -1, 1

b. False Zero Crossings

Length 14

-1, -1, -1, -1, 1, -1, 1, -1, 1, -1, 1, -1, 1, 1

Length 16

-1, -1, -1, -1, -1, 1, -1, 1, -1, 1, -1, 1, -1, -1, 1, 1

Length 18

-1, -1, -1, -1, -1, 1, -1, 1, -1, 1, -1, 1, -1, 1, -1,
-1, 1, 1

Length 19

-1, -1, -1, -1, 1, -1, 1, -1, 1, -1, 1, -1, 1, -1, -1,
1, 1, -1, 1

codes, from selected ones of length up to 20. In this way, any code of interest of length L can be extended in a manner which maintains the particular characteristics of the sequence and which results in sequences of length L^2. Subroutine EXTEND can be applied to the main program of Appendix A-1 before shaping takes place.

Figures 13a through 13c show the results of subroutine EXTEND on the 7-bit m-sequence (without any shaping). The results obtained were not particularly interesting for the sequences considered.

D. EXPERIMENTAL INVESTIGATION

1. System Design

In this section the experimental system used to verify the computer results is presented. With this technique, it is possible to generate a variety of pulse shapes. Of particular interest are the raised sine, triangular and ramp shaped pulses of the sequence. Included here are the results (photographs of the ACF and spectra) of the experimental effort.

The block diagram of the experimental system is shown in Fig. 14. A discussion of the circuitry is in Appendix C.

2. Waveforms

The photographs of Figure 15 show the results obtained by the available pulse shapes with the 7-bit m-sequence.

Each photograph contains two traces; one trace shows the rectangular pulse sequence and the other the shaped pulse sequence.

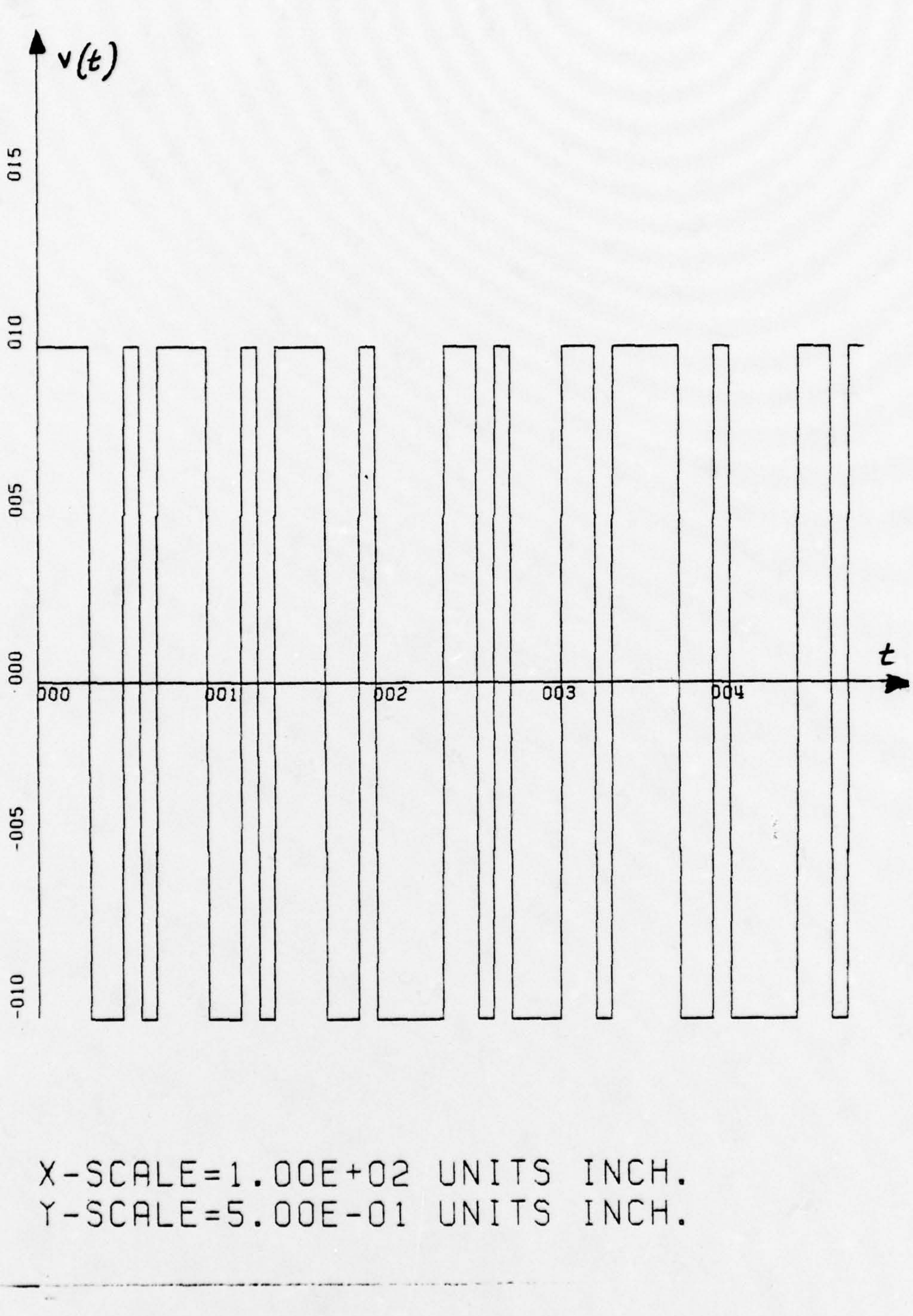
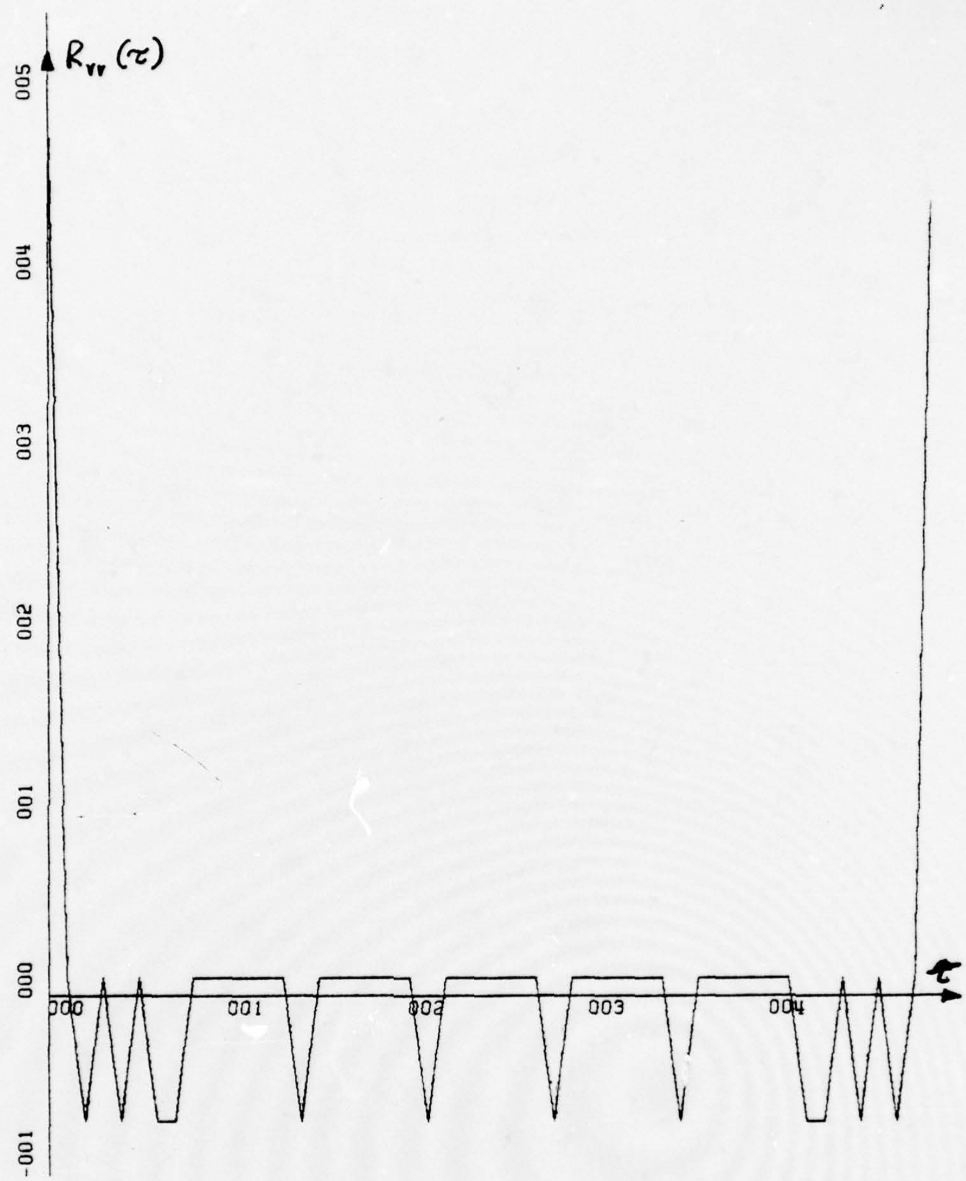


Fig. 13a. THE RECTANGULAR SHAPE 7-BIT m-SEQUENCE EXTENDED TO LENGTH $L = 7^2 = 49$.



X-SCALE=1.00E+02 UNITS INCH.
Y-SCALE=1.00E+02 UNITS INCH.

Fig. 13b. THE ACF OF THE RECTANGULAR SHAPE 7-BIT m-SEQUENCE EXTENDED TO LENGTH $L = 7^2 = 49$.

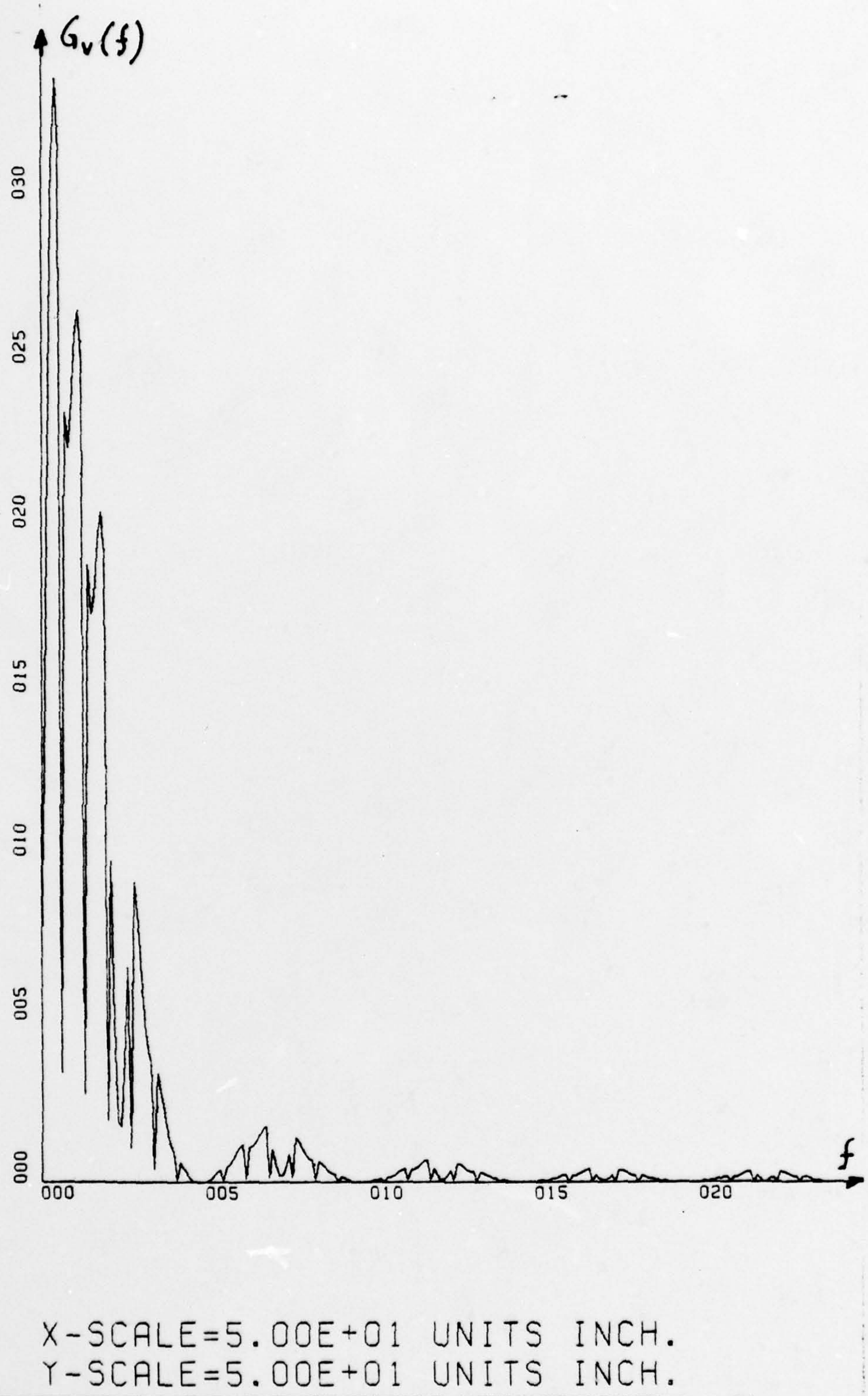


Fig. 13c. THE POWER SPECTRUM OF THE RECTANGULAR SHAPE 7-BIT m-SEQUENCE EXTENDED TO LENGTH $L = 7^2 = 49$.

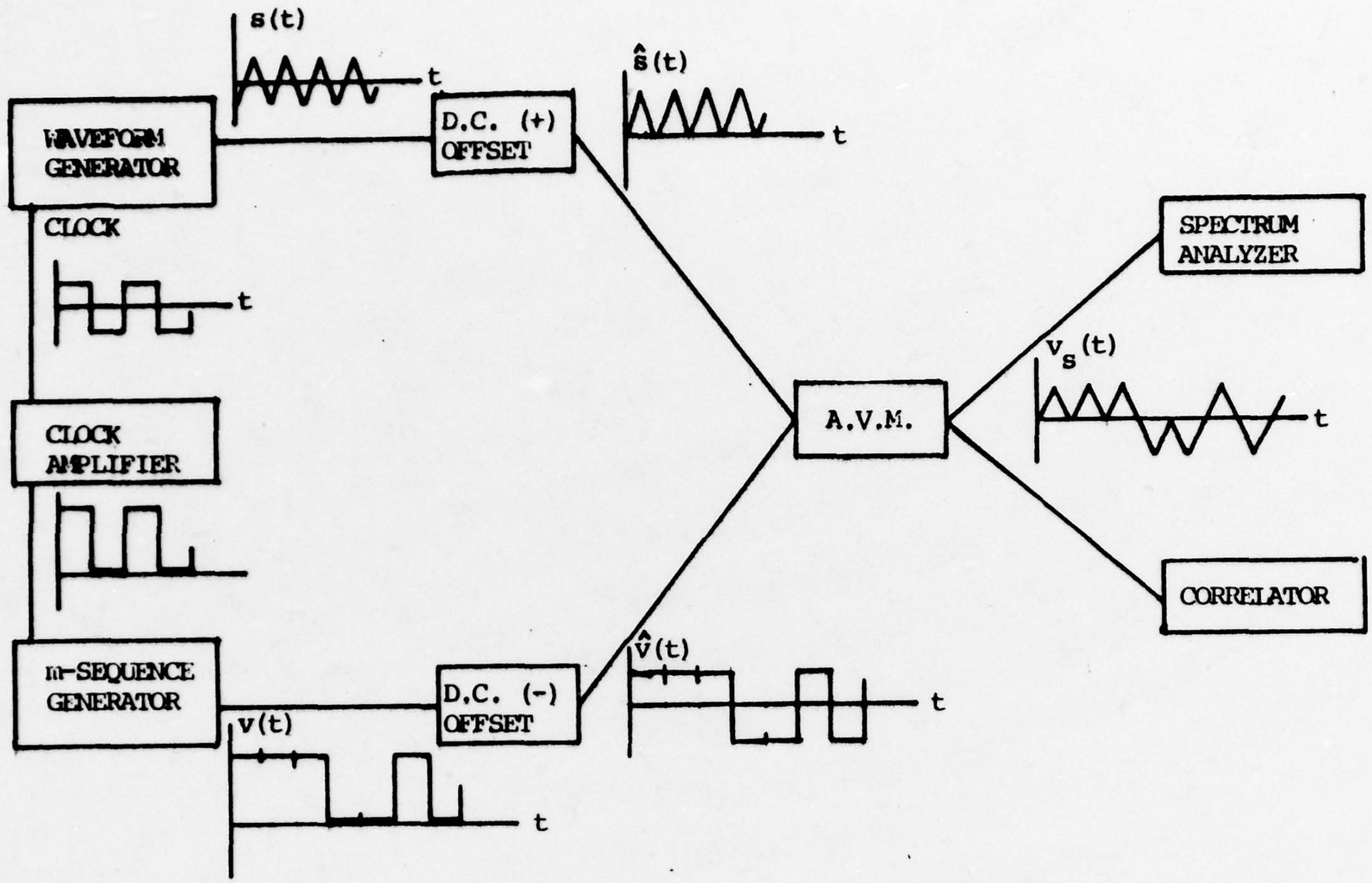
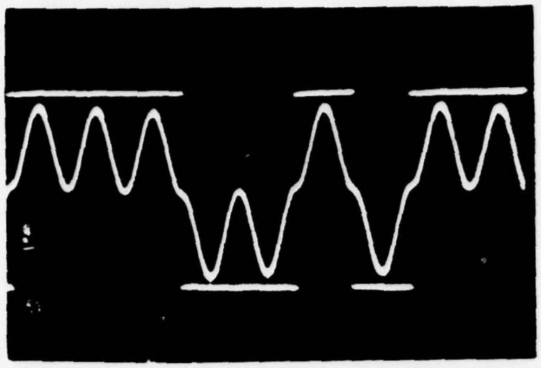
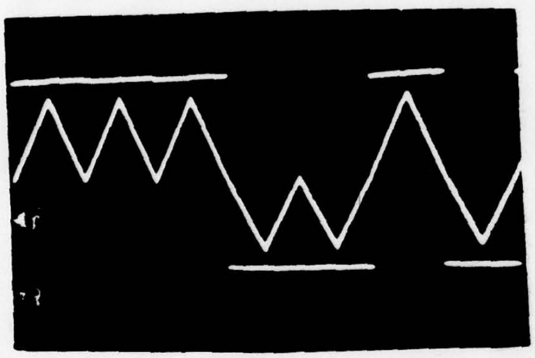


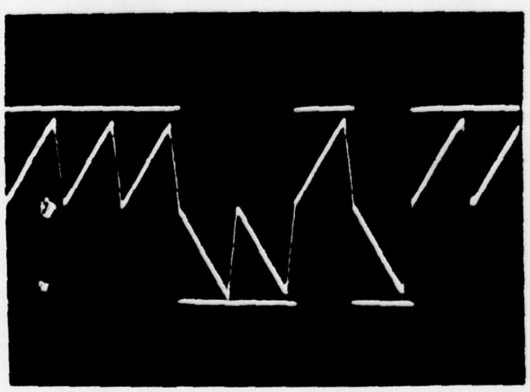
Fig. 14. BLOCK DIAGRAM OF THE EXPERIMENTAL SYSTEM.



(a) Raised sine shape

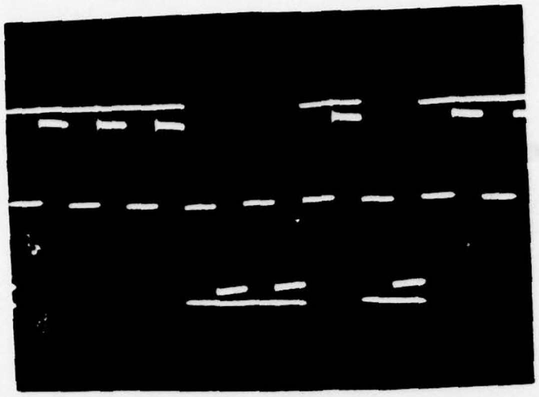


(b) Raised triangular shape

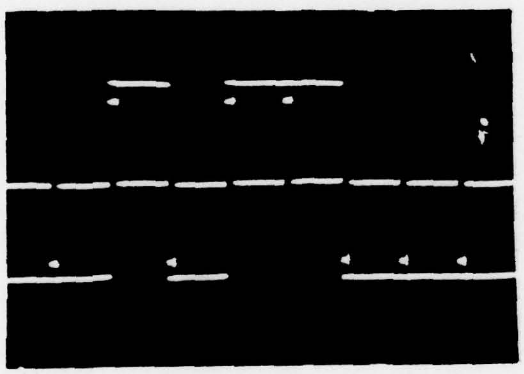


(c) Raised ramp shape

Fig. 15. PHOTOGRAPHS OF THE 7-BIT m-SEQUENCE OF VARIOUS SHAPES.



(d) Rectangular (50%) shape



(e) Rectangular (15%) shape

Fig. 15. CONTINUED.

The shapes shown are:

* Raised sine
* Raised triangle
* Raised ramp
* Rectangular (50% duty cycle)
* Rectangular (15% duty cycle)

3. <u>Sequence Autocorrelation Functions</u>

Fig. 2c indicates that the maximum value of the ACF of a sequence is related to the number of pulses of the sequence. Larger values of this maxima (main lobe) improve the detection of the sequence.

Many ways of calculating or implementing the ACF of a rectangular sequence are known. But for the case of a "shaped" sequence there are no ways of predicting the exact form of the ACF, since it is no longer piecewise linear. A similarity though is expected in the relation between main lobe and side-lobe levels.

In the computer search, the ACF of the examined sequences were calculated and plotted, and these results are confirmed in the laboratory.

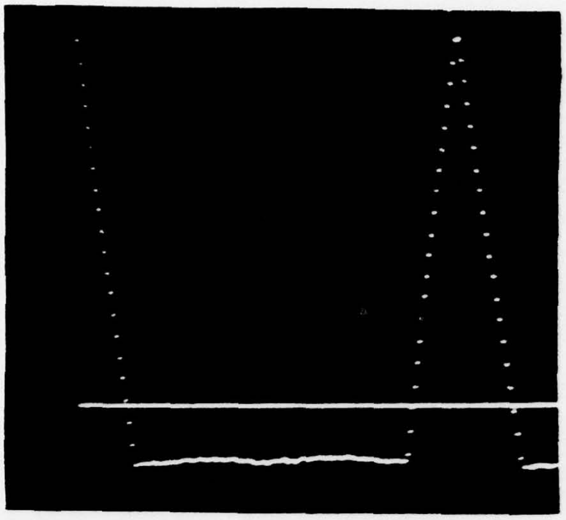
It is clear that "shaping" a sequence of the same voltage (for comparison) as the rectangular one will result in a loss of the energy content of the pulses, causing a decrease of the peak value of the corresponding ACF, which reduces the detectability of the signal.

The actual shape, peak value and side lobe level of shaped sequences are examined in this part of the

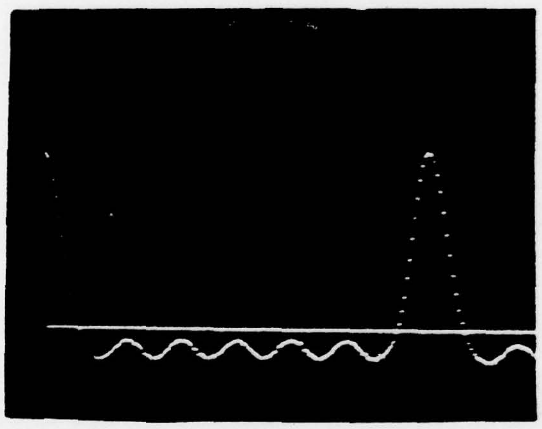
project. Detailed descriptions of the operating conditions are given in Appendix C.

The results are displayed on a HP 1220A oscilloscope, and the pictures taken under the same scale are shown in Figs. 16a through 16f.

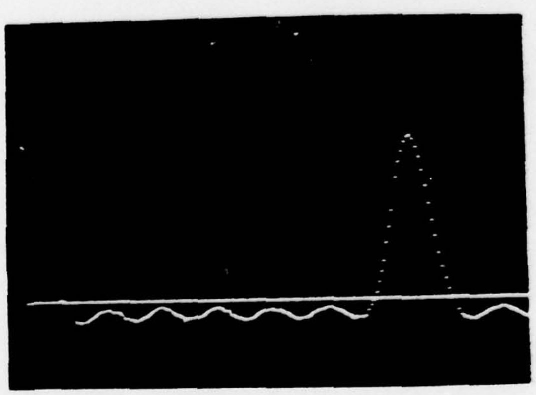
In these pictures, the input is a 1 volt peak to peak 7-bit m-sequence. The correlator setting is linear display, sample increment 20 μs and summations 128 x 1024.



(a) Rectangular shape; peak is +1.65V, minimum is -230 mV.

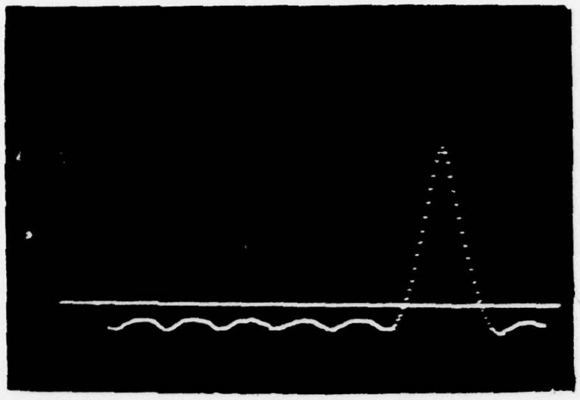


(b) Raised sine shape; peak is +0.80V, minimum is -130 mV

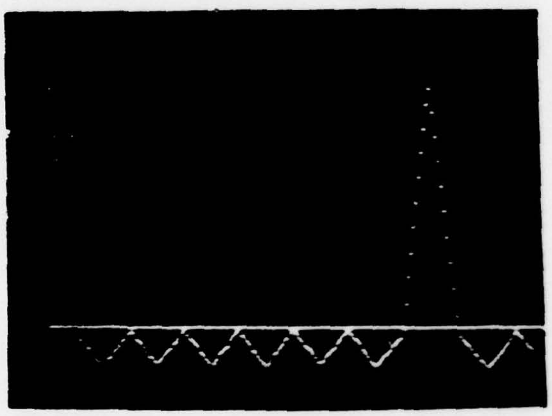


(c) Raised triangular shape; peak is +0.72 V, minimum is -125 mV.

Fig. 16. PHOTOGRAPHS OF THE ACF OF THE 7-BIT m-SEQUENCE OF VARIOUS SHAPES.

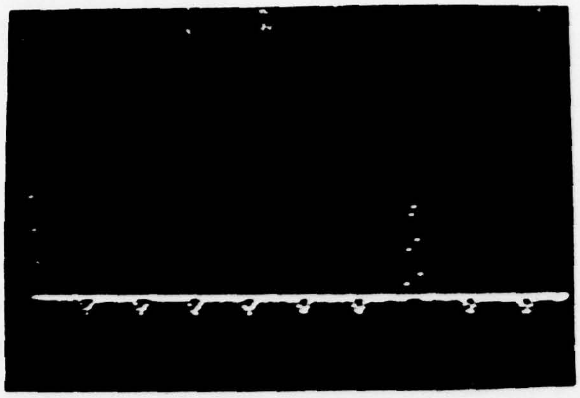


(d) Raised ramp; peak is +0.71 V, minimum is -120 mV.



(e) Rectangular (50%); peak is +1.1 V, minimum is -125 V.

Fig. 16. CONTINUED



(f) Rectangular (15%); peak is +0.33 V, minimum is -45 mV.

Fig. 16. CONTINUED

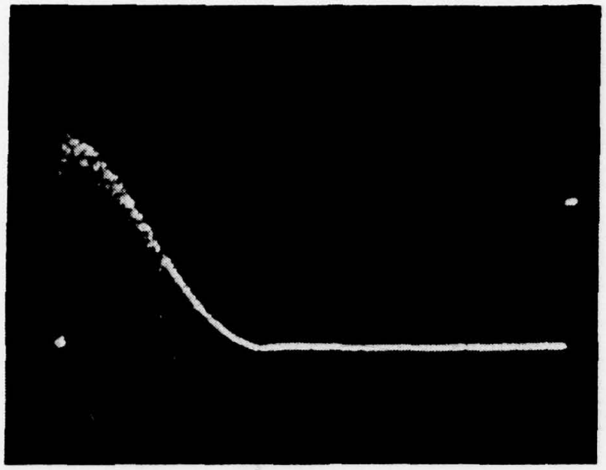
We observe the known relation between pulse-energy content and ACF. We notice that the raised sine, triangle and ramp shaped pulses have approximately the same shape and peak values of their ACF.

In the limited duty cycle rectangular pulses, comparing the original sequence with the 50% and 15% duty cycle shapes, we observe that the peak value is approximately higher by 1.375 of the corresponding duty factor percentage.

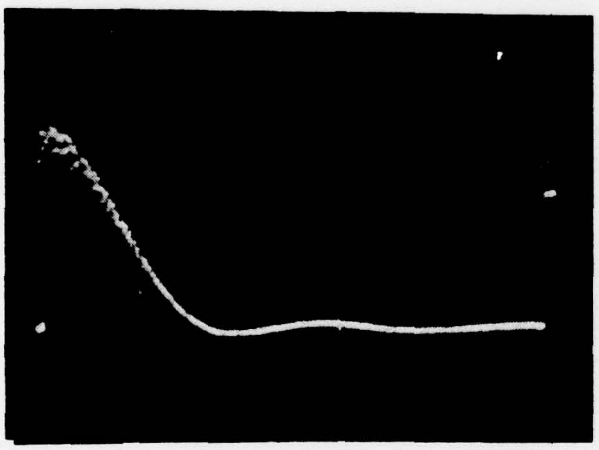
A conclusion is that all the sequence shapes have the same form of ACF: that is, a high positive peak value at $\tau = 0$, and small negative or zero values for $\tau \neq 0$. Therefore these shaped sequences are also usable in signal detection applications.

4. <u>Sequence Spectra</u>

Figures 17 through 19 are a series of pictures of spectra of m-sequences of various frequencies. Those were taken from the SPECTRAL DYNAMICS SO-335 Spectrum Analyzer

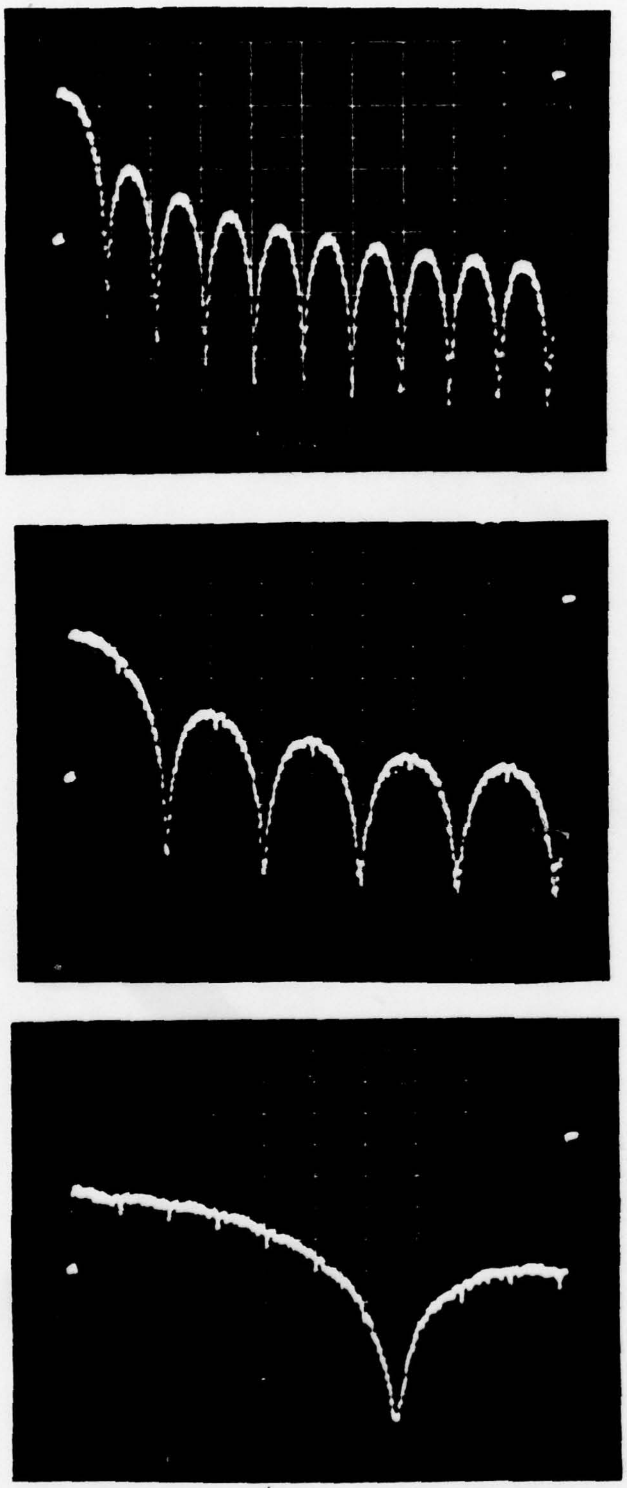


(a) Raised sine



(b) Raised triangle

Fig. 17. PHOTOGRAPHS (DETAIL) OF THE AVERAGED SPECTRA (LINEAR DISPLAY) OF THE 127-BIT m-SEQUENCE. (f = 10 kHz, 128 averages, 20 dB output gain)

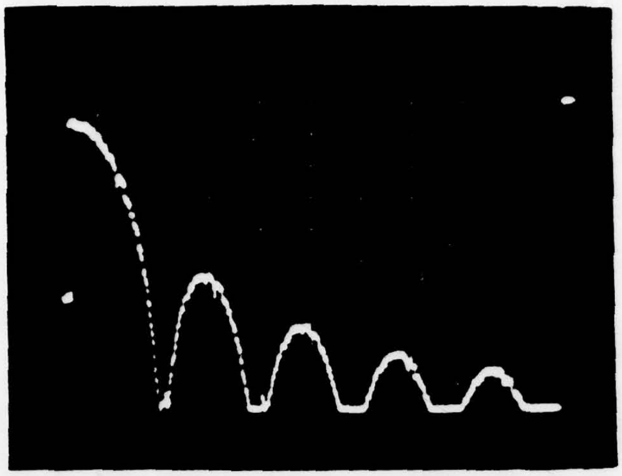


(a) Original rectangular (100% duty cycle)

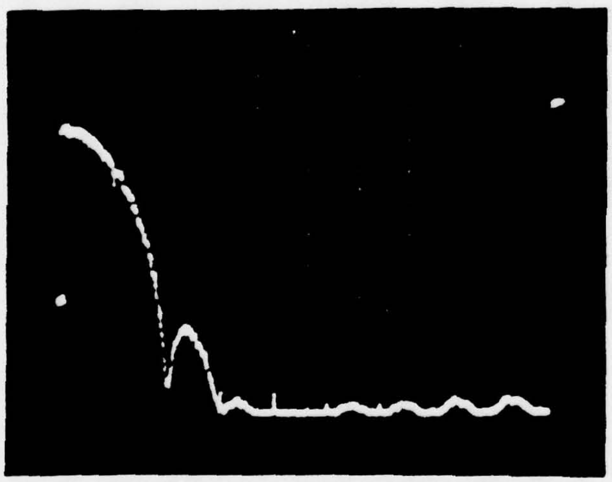
(b) Rectangular (50% duty cycle)

(c) Rectangular (15% duty cycle)

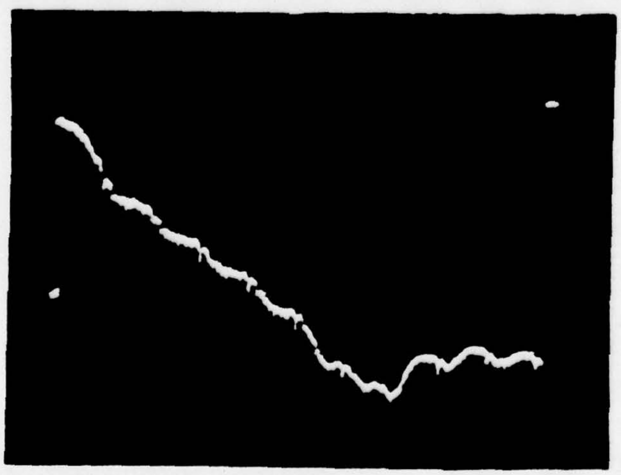
Fig. 18. PHOTOGRAPHS OF THE 127-BIT m-SEQUENCE (LOG. DISPLAY); f = 5 kHz, 64 averages, 10 dB output gain.



(d) Raised triangle

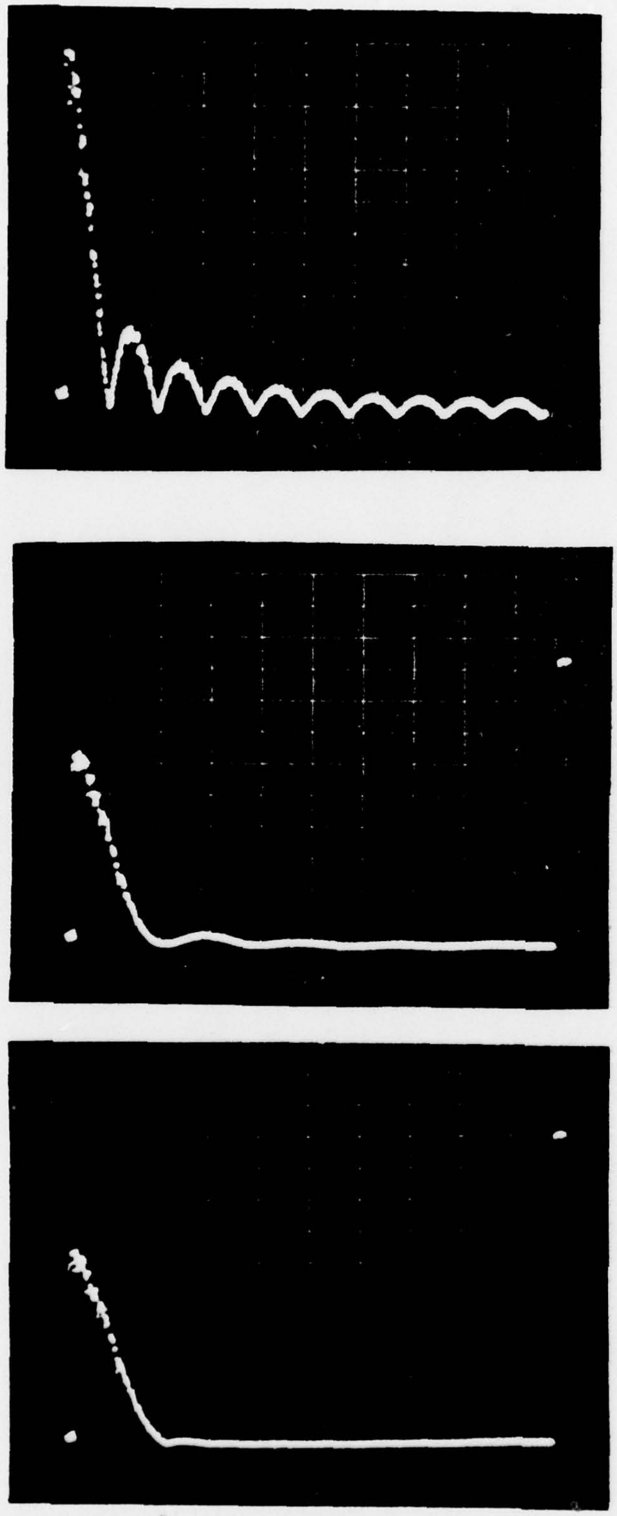


(e) Raised sine



(f) Ramp

Fig. 18. CONTINUED



(a) Original rectangular (100% duty cycle)

(b) Raised triangle

(c) Raised sine

Fig. 19. PHOTOGRAPHS OF SEQUENCE OF FIG. 18, BUT WITH LINEAR DISPLAY.

with a window of 50 kHz. These results of Fig. 17 can be compared with Figures 7c and 8c, which are the corresponding computer results.

The important conclusion is that the laboratory results are in good agreement with the computer results. We also observe that different pulse shapes give quite different spectra.

Appendix C contains additional photographs.

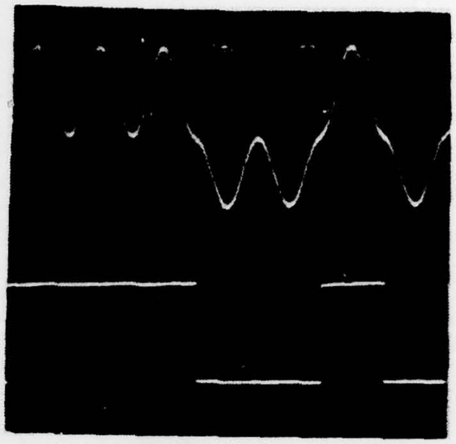
In Figs. 20 through 24, photographs of the 7-bit m-sequence of various shapes are shown (in log display) along with their corresponding spectra.

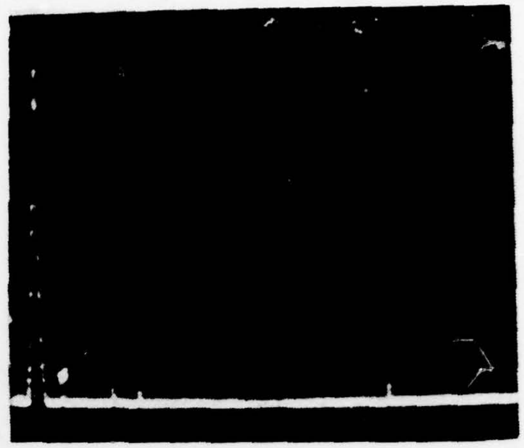
Also, for reference, the time domain photographs of the investigated sequence are presented (part a of the figures) as well as the spectrum of the waveform used for shaping the rectangular pulses (part b of the figures). In parts c and d of these figures, the upper trace is the spectrum of the shaped sequence.

In Fig. 20(b) we observe the 2.5 kHz fundamental frequency of the raised sine pulse train. The low level components are harmonics present at the output of the function generator.

In Figs. 20(c) and 20(d) the spectra of the shaped sequence is shown, in comparison with the $(\frac{\sin x}{x})^2$ spectrum of the original sequence for two different frequencies of 5 kHz and 2.5 kHz.

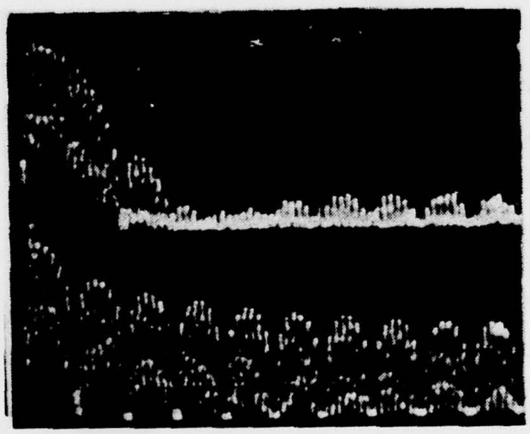
The large concentration of energy at low frequencies may be observed, due to the fundamental of the raised sine.

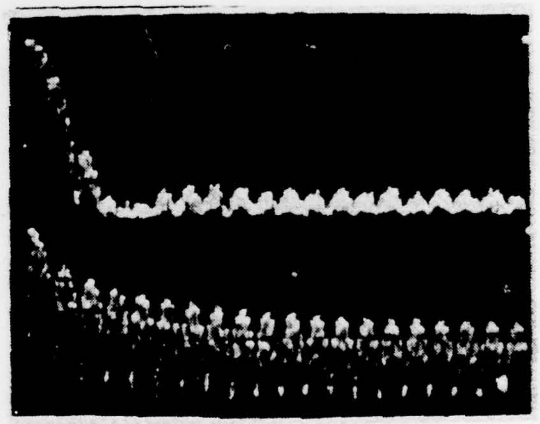




a) The shaped sequence and the original.

b) The frequency components of the sinusoidal: f = 2.5 kHz.





c) The spectra when f = 5 kHz.

d) The spectra when f = 2.5 kHz.

Fig. 20. THE RAISED SINE SHAPE 7-BIT m-SEQUENCE. Four averages, Ø dB output gain, window of 50 kHz.

This results in a main lobe of bandwidth equal to twice the clock rate, a first side lobe of reduced level, and minor other side lobes.

In Fig. 21(b) we observe the fundamental frequency of the triangle pulse train at 2.5 kHz, as well as the harmonics separated by 5 kHz.

In Figs. 21(c) and 21(d) the spectrum of the shaped sequence is shown in comparison with the $(\frac{\sin x}{x})^2$ spectrum of the unshaped sequence, under two different frequencies of 5 kHz and 2.5 kHz.

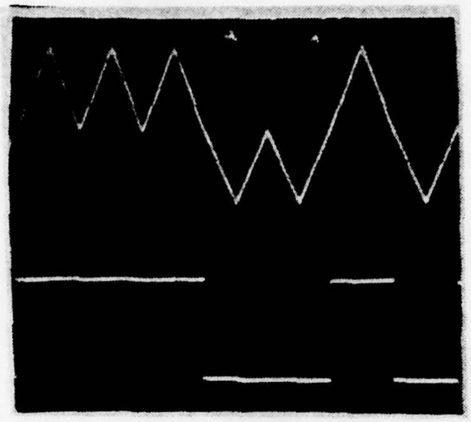
The resulting spectrum is strongly influenced by the frequency components of the raised triangle.

We observe that the bandwidth of all lobes of the shaped sequence spectrum are double those of the rectangular shape (original) sequence. Consequently all nulls appear to correspond to twice the actual clock frequency. Also, the side lobe level has been significantly reduced.

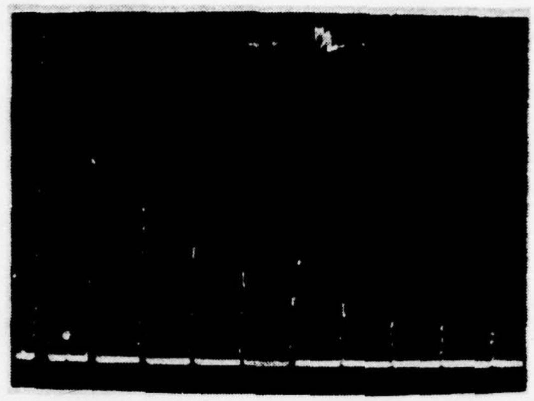
In Fig. 22(b) we observe the fundamental frequency of the ramp pulse train at 2.5 kHz and the harmonics separated by 2.5 kHz. The nulls of the overall form of the spectrum appear approximately every 7 kHz.

In Figures 22(c) and (d) the spectrum of the shaped sequence is compared with the spectrum of the original sequence for frequencies of 5 kHz and 2.5 kHz.

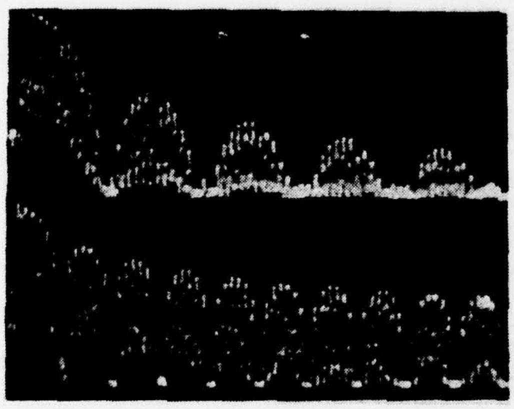
The resulting spectrum follows the general shape of the spectrum of the periodic ramp (Fig. 22(b)). We again



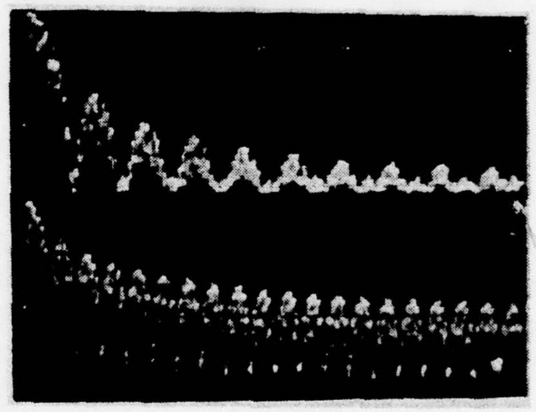
a) The shaped sequence and the original.



b) The frequency components of the raised triangle: f = 2.5 kHz.

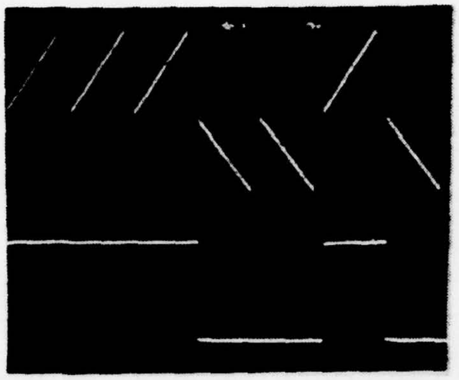


c) The spectra when f = 5 kHz.

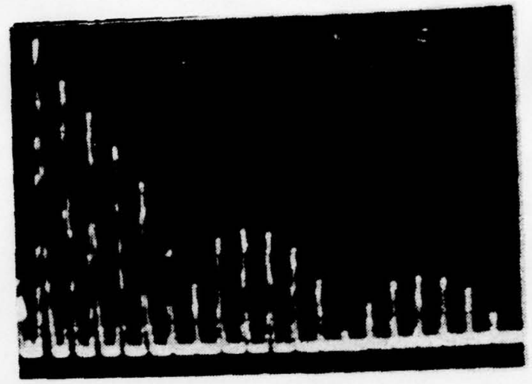


d) The spectra when f = 2.5 kHz.

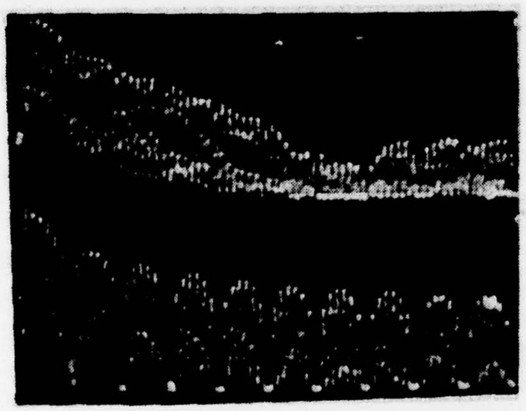
Fig. 21. THE RAISED TRIANGLE SHAPE 7-BIT m-SEQUENCE. Four averages, 0 dB output, window of 50 kHz.



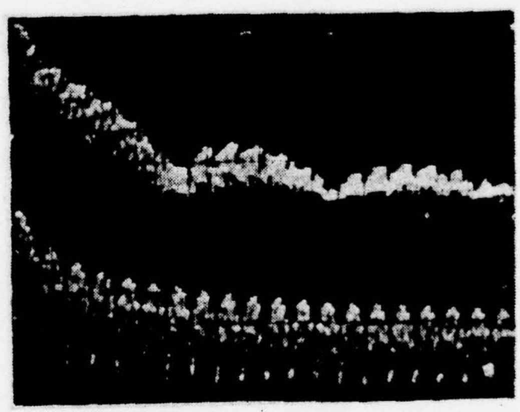
a) The shaped sequence and the original



b) The frequency components of the raised ramp



b) The spectra when f = 5 kHz.



d) The spectra when f = 2.5 kHz.

Fig. 22. THE RAISED RAMP SHAPE 7-BIT m-SEQUENCE.
Four averages, 0 dB output, window of 50 kHz.

observe a concentration of energy at low frequencies. The bandwidth of both main lobe and side lobes has been equally enlarged and the side lobe level has been significantly reduced.

The nulls appear approximately 17 kHz apart, giving an indication of a clock frequency much higher than the true one.

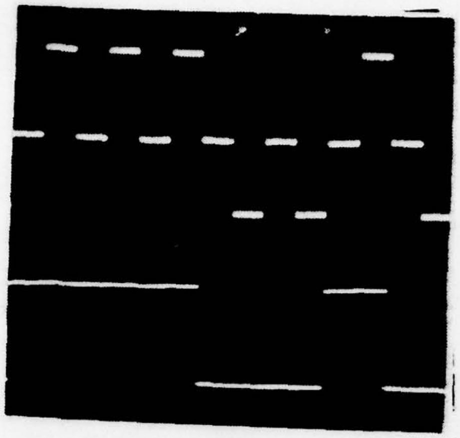
Figure 23(b) shows the frequency component of a rectangular, 50% duty cycle pulse train. Here the fundamental frequency is at 2.5 kHz and the harmonics occur at 5 kHz intervals. There are also minor even harmonic components.

In Figs. 23(c) and 23(d) the spectrum of the shaped sequence is compared with the spectrum of the unshaped sequence for frequencies of 5 kHz and 2.5 kHz.

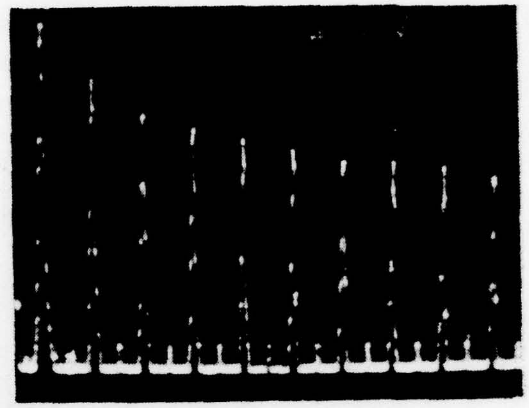
The spectrum of this shaped sequence is a regular $(\frac{\sin x}{x})^2$ spectrum with nulls at twice the actual clock frequency and double the bandwidth of main and side lobes.

Fig. 24 shows results similar to those of Fig. 23. The main difference appears to be the increase of lobe bandwidths by a factor equal to the inverse of the duty cycle of the shaping waveform (i.e., $\frac{1}{.15} = 6.6$) as well as the indication of a clock frequency higher than the actual by the same factor.

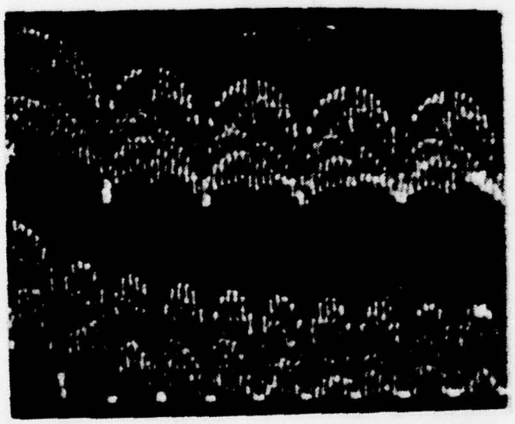
From the previous photographs of the spectra of various shaped sequences, we conclude that shaped m-sequences



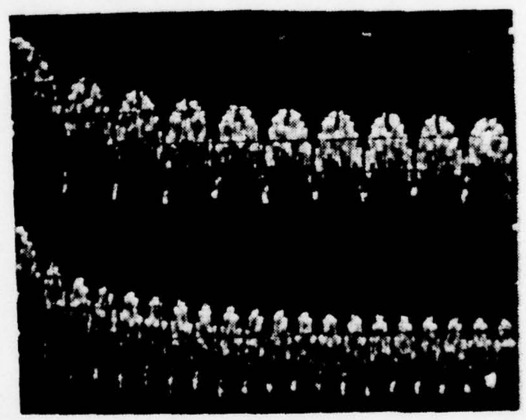
a) The shaped sequence and the original



b) The frequency components of the 50% duty cycle rectangular



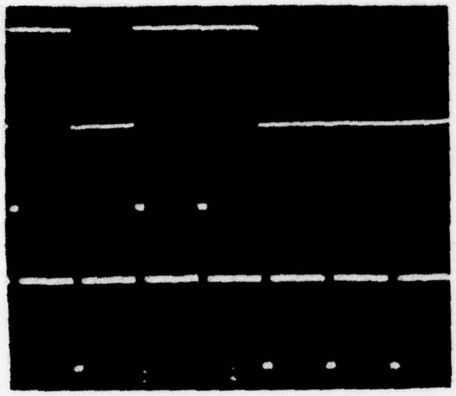
c) The spectra when $f = 5$ kHz.



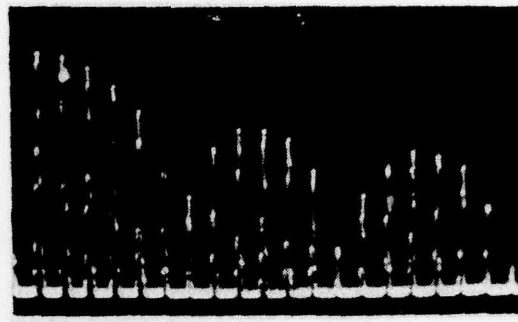
d) The spectra when $f = 2.5$ kHz.

Fig. 23. THE 50% DUTY CYCLE RECTANGULAR 7-BIT m-SEQUENCE. Four averages, 0 dB output, window of 50 kHz.

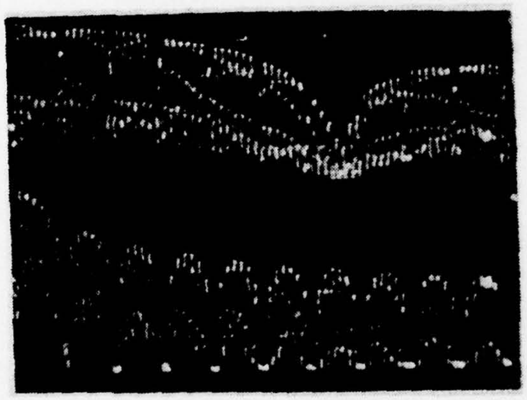
can have spectra with significant concentration of power in the low-frequencies, with small side lobes (raised sine shape), of irregular form (ramp), or with false indication of clock frequency (triangle, rectangular 50% duty cycle shapes).



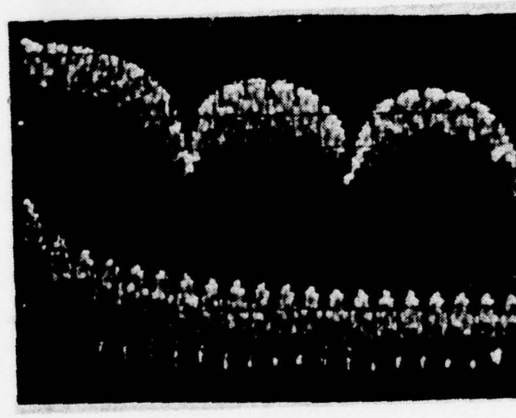
a) The shaped sequence and the original



b) The frequency components of the 15% duty cycle rectangular



c) The spectra when f = 5 kHz.



d) The spectra when f = 2.5 kHz.

Fig. 24. THE 15% DUTY CYCLE RECTANGULAR 7-BIT m-SEQUENCE. Four averages, 0 dB output, window of 50 kHz.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The study presented in this report had as an initial objective the discovery of binary sequences having spectra which, by proper pulse shaping, could be made nearly uniform.

The two main areas of research were:

a. The investigation of the effect of pulse shaping on m-sequences, and

b. The search of binary sequences of all lengths through 20 bits having spectra of interest.

Some of the interesting results of this study are:

1. The creation of a computer program to shape any sequence, to plot the sequence, and to calculate and plot the autocorrelation function and spectrum of the sequence.
2. Realization of a system which can produce sequences having various pulse shapes.
3. Discovery of sequences having interesting spectra. For example: some shapes and sequences have spectra with very small side lobe levels, or the spectra have no discernable nulls. Some shaped sequences have spectra with nulls not simply related to the clock frequency. Also, some shaped sequences have power concentrated at low frequencies.

One interesting result is that the shaped m-sequences have autocorrelation functions and spectra of such a form that make them usable in particular radio systems (radar, sonar, spread spectrum).

B. RECOMMENDATIONS

1. Additional waveshapes can be created. Using the experimental equipment of this study, a more extended search for spectra of interest can be conducted.
2. Using the program presented in Appendix B, a further computer investigation can be conducted for arbitrary sequences longer than 20 bits.
3. The laboratory setup could be connected to a microcomputer used to generate long sequences that are not m-sequences. That source and a spectrum analyzer may provide the ability to rapidly examine spectra.

APPPENDIX A

CALCULATION OF THE AUTOCORRELATION FUNCTION (ACF) OF A BINARY SEQUENCE

The ACF $R_{vv}(\tau)$ of a voltage v(t) is an even function, which has its maximum value (level of the main lobe) at $\tau = 0$. Secondary maxima are the side lobe levels.

The shape of the ACF of a binary sequence v(t) with rectangular pulses is easily obtained by letting V = 1 and $\varepsilon = 1$.

For example, to form the ACF of the periodic sequence

$$A = +1, +1, -1, +1 \quad \text{or} \quad A = + + - +$$

the sequence is written, and its delayed version is written below.

For example, when $\tau = 0$, there is no delay and we have

$$\begin{array}{c} + + - + \\ + + - + \underline{+ + - +} + + - + \\ + + + + \quad \rightarrow \; 4 \end{array}$$

In each position, the corresponding elements are compared. If the elements are alike, this is noted with a +. Unlike elements are assigned a −. The number of like elements less the number of unlike elements is the value of the ACF

for this value of delay τ. Here, all corresponding elements are the same, and thus the ACF has value equal to 4.

Now, when $\tau = 1$, a shift is made as follows:

$$\begin{array}{l} \qquad\quad + + - + \\ + + - \underline{+ + + -} + + + \\ \qquad\quad + + - - \quad \rightarrow 0 \end{array}$$

By the same method we see that the value of the ACF when $\tau = 1$ is 0.

Similarly, for $\tau = 2$, we have

$$\begin{array}{l} \qquad + + - + \\ + + \underline{- + + +} - + \\ \qquad - + - + \quad \rightarrow 0 \end{array}$$

which gives 0 again.

The next position at $\tau = 3$ becomes

$$\begin{array}{l} \quad + + - + \\ + \underline{+ - + +} + - + \\ \quad + - - + \quad \rightarrow 0 \end{array}$$

which gives 0.

Finally, the position $\tau = 4$ corresponds to the period T of v(t) and so the value of the ACF is the same as the

value at the origin since $R_{VV}(kT) = R_{VV}(0)$, k an integer.

Since $R_{VV}(\tau)$ is even, we need evaluate only the "one-sided" ACF of the sequence A, which can be written as:

$$R_A(\tau) \;=\; 4,\ 0,\ 0,\ 0,\ 4,\ \ldots$$

We notice that the "one-sided" ACF can be completely described by 5, or in general L+1 points, where L is the number of elements in one period of the sequence. The function $R_{VV}(\tau)$ is obtained for all values of τ by connecting with a straight line the values obtained in the preceding discussion when τ is 0, 1, 2, ..., L . This analysis leads to the conclusion that it is possible to define a sequence of L elements having a specified ACF, with a set of equations. Consider a periodic sequence of L elements $x_1, x_2, x_3, \ldots, x_L$ of unity amplitude and duration ($V = \pm 1$, $\varepsilon = 1$). The ACF is computed by solving the following equations, which actually form a system:

$$\begin{array}{lllllll}
\tau = 0 & x_1^2 & + x_2^2 & + x_3^2 & + \ldots + & x_L & = L \\
\tau = 1 & x_1 x_L & + x_2 x_1 & + x_3 x_2 & + \ldots + & x_L x_{L-1} & = \alpha \\
\tau = 2 & x_1 x_{L-1} & + x_2 x_L & + x_3 x_1 & + \ldots + & x_L x_{L-2} & = \beta \\
\tau = 3 & x_1 x_{L-2} & + x_2 x_{L-1} & + x_3 x_L & + \ldots + & x_L x_{L-3} & = \gamma \\
\vdots & \ldots & \ldots & \ldots & \ldots & \ldots & \\
\tau = L-1 & x_1 x_2 & + x_2 x_3 & + x_3 x_4 & + \ldots + & x_L x_1 & = y \\
\tau = L & x_1^2 & + x_2^2 & + x_3^2 & + \ldots + & x_L^2 & = L
\end{array}$$

We notice that a system of L+1 equations has been formed. The left hand side corresponds to the sums of all combinations by two of the sequence's elements (in this case ±1) and, the right hand side corresponds to integers (L, a, β, γ ... y) with absolute values equal or less than L.

The last equation, which is the same as the first equation, results from the periodic nature of the ACF of periodic sequences. Unfortunately, this method has little value for two reasons: First, a general solution for the system of equations is not known. Second, the ACF does not uniquely define a sequence, because the ACF is only a partial description of the sequence. For example, all m-sequences of length L have the same ACF, as mentioned in Section II.D.2 of this report.

APPENDIX B

COMPUTER PROGRAMS

1. Program to shape a sequence and then calculate and plot its ACF and power spectrum. This is the main program on page 86.

Using the technique discussed in Appendix A, the algorithm for a FORTRAN computer program is constructed in the following steps:

a. Provide the sequence for investigation as the data deck for the program. In this particular search the m-sequences examined are:

(1) L = 7 : 1,1,1,-1,-1,1,-1.

(2) L = 63: -1,-1,-1,-1,-1,-1,1,1,1,1,
1,-1,1,1,1,1,-1,-1,1,
1,1,-1,1,-1,1,1,-1,-1,
-1,-1,1,-1,1,1,1,-1,-1,-1,
1,1,-1,1,1,-1,1,-1,-1,
1,-1,-1,-1,1,-1,-1,1,1,
-1,-1,1,-1,1,-1,1

(3) L = 127: 1,-1,-1,-1,-1,-1,-1,1,-1,-1,-1,-1,-1,
1,1,-1,-1,-1,-1,1,-1,1,-1,-1,-1,1,1,
1,1,-1,-1,1,-1,-1,-1,1,-1,1,1,-1,-1,1,
1,1,-1, 1,-1,1,-1,-1,1,1,1,1,1,-1,1,-1,
-1,-1,-1,1,1,1,-1,-1,-1,1,-1,-1,1,-1,
-1,1,1,-1,1,1,-1,1,-1,1,1,-1,1,1,1,1,-1,
1,1,-1,-1,-1,1,1,-1,1,-1,-1,1,-1,1,1,1,
-1,1,1,1,-1,-1,1,1,-1,-1,1,-1,1,-1,1,
-1,1,1,1,1,1,1.

These data are punched in each card as 1. or -1, starting from the first column of the card. The end of the data is denoted in the deck by one card punched with a 2.

b. To create longer sequences, the Subroutine EXTEND is constructed. The procedure is to substitute for each 1 of the data, the sequence itself and for each -1 by the complement of the sequence.

For example, consider the sequence

$$A = 1, 1, -1$$

$$(1,1,-1)\ (1,1,-1)\ (-1,-1,1)$$

which results in the longer sequence

$$A_X = 1,1,-1,1,1,-1,-1,-1,1.$$

Thus, if so desired (in the program, with the card: CALL EXTEND (ISG,LS)), a sequence of length L can be extended to length L^2.

The subroutine EXTEND is presented on page 87.

c. The sequence's pulses are shaped individually with the desired waveshape. Each shape has a unity peak amplitude and is described by its equation in FORTRAN. This is done by constructing Subroutine WAVE which is described on page 88.

d. The resulting "shaped" m-sequence is then plotted using Subroutine DRAWP which is provided by the computer center.

e. The periodic ACF of the "shaped" sequence is then calculated. By the point-to-point multiplication of predetermined sample points per pulse, the subroutine PANOS is constructed, based on the preceding ACF analysis, and is described on page 89 .

f. The resulting points are numerically printed out and a plot of the ACF is provided by subroutine DRAWP.

g. The power spectrum of the "shaped" sequence is then calculated and plotted as follows:

(1) Compute the Fourier transform H(f) of the Periodic ACF $R(\tau)$, using FFT.

$$H(f) = \sum_{i=0}^{N-1} R(\tau)e^{-j2\pi f\tau/i}$$

(2) Change the sign of the imaginary part of H(f) to obtain H*(f).

(3) Compute and normalize the product H(f)·H*(f) to obtain the power spectrum S(f):

$$S(f) = \frac{1}{N} \cdot H(f) \cdot H^*(f)$$

(4) Print out the resulting points.

(5) Plot the power spectrum using subroutine DRAWP.

This procedure is accomplished by constructing the subroutine XFM, which is described on page 90 .

The main body of the program is shown on page 86.

In the above process the computer time appears to be a limitation. In the longer sequences, the number of samples per pulse has to be reduced from the original 20 samples to 10 samples so that the total process can be completed in less than 30 minutes of computer time.

The complete computer printout and plots for the unshaped 7-bit m-sequence is shown in Figures 25 through 26.

The printout and plots for the same m-sequence shaped with the triangular function is shown in Figures 27 through 28.

The printout for the 7-bit m-sequence of Fig. 25 when extended is shown in Fig. 29 and the corresponding plots of the extended sequence when shaped with the raised-sine are shown in Figure 30.

PROGRAM #1 THE MAIN BODY

```
CECLARATICNS

      INTEGER*4 ITB(12)/12*C/
      REAL*4    RTB(28)/28*C.C/,STB(28)/28*0.C/
      DIMENSICN ISG(3000),W(3000),X(3000),AC(3000)
      LOGICAL PERIOD

READ AND WRITE DATA

      READ (5,5C) NS
 50   FORMAT (I2)
      READ (5,15C) PERIOD
150   FORMAT (L1C)
      WRITE (6,17C) PERIOD
170   FORMAT (' PERICD=',L1C)
      LS=1
200   READ (5,21C) TEMP
210   FORMAT (F1C.0)
      ISG(LS)=IFIX(TEMP)
      IF (ISG(LS).EQ.2)  GC TC 250
      WRITE (6,220) ISG(LS)
220   FORMAT (1X,I2)
      LS=LS+1
      GC TC 2CC                         (optional)
250   LS=LS-1                                 CALL EXTEND (ISG,LS)

SHAPE THE PULSES AND PLOT THE SEQUENSE

      CALL WAVE (W,LW,ISG,LS,NS)
      CO 270 I=1,LW
270   X(I)=I
      CALL DRAWP (LW,X,W,ITB,RTB)

CALCULATE,WRITE AND PLOT THE ACF

      CALL  PANCS  (W,LW,AC,PERICD)
      WRITE (6,3CC)
300   FORMAT (' AUTC CORRELATICNS : ')
      LX=LW
      CO 11 I=1,LX
 11   X(I)=I-1
      WRITE  (6,4CC)  (X(I),AC(I),I=1,LX)
400   FORMAT   (1X,F5.0,1X,F12.5)
      CALL DRAWP (LX,X,AC,ITB,RTB)

CALCULATE,WRITE AND PLOT THE POWER SPECTRUM

      CALL XFM (AC,LX,LS)
      STCP
      END
```

```
NCTES
-------

NS= SAMPLE PCINTS PER PULSE

PERICD=TRUE FCR PERIODIC ACF,CR FAULSE FOR APERICCIC ACF

TEMP = CATA PULSES , 1. CR -1.

END CATA CECK BY 2.
```

```
      SUBROUTINE EXTEND (ISG,LS)
      DIMENSION ISG(1),ISEL(100)
      INTEGER FLPFLP
      DO 10 I=1,LS
   10 ISEL(I)=ISG(I)
      NSIGF=0
      I1=1
      DO 77 I7=1,LS
      FLPFLP=ISIGN(I1,ISEL(I7))
      WRITE (6,200) FLPFLP
  200 FORMAT (1X,I10)
      DO 66 I6=1,LS
      NSIGF=NSIGF+1
      ISG(NSIGF)=FLPFLP*ISEL(I6)
      WRITE (6,300) ISG(NSIGF)
  300 FORMAT (10X,I10)
   66 CONTINUE
   77 CONTINUE
      LS=LS**2
      WRITE (6,500) (ISG(J),J=1,LS)
  500 FORMAT (1X,60I2)
      RETURN
      END
```

```
      SUBROUTINE WAVE (W,LW,ISG,LS,NS)

      DIMENSION W(1),ISG(1)

C THE FOLLOWING CARD DEFINES THE WAVEFORM
      WF(X)=1.

      LW=LS*NS
      WRITE (6,10) LS,NS,LW
   10 FORMAT (3I10)
      DO 100 I=1,LW
  100 W(I)=WF(FLOAT(I)/NS)*ISG(1+(I-1)/NS)
      RETURN
      END
```

NOTES

```
WF(X) DEFINES THE SHAPING WAVEFORM

WF(X)=1. CORRESPONDS TO RECTANGULAR

WF(X)=(1.-SIN(1.570786+6.283185*X))*.5
                  TO RAISED SINE

WF(X)=10.*AMIN1(.2*AMOD(X,1.),.2*(1.-AMOD(X,1.)))
                  TO TRIANGLE

WF(X)=1.*EXP(-.5*(AMOD(5.16*X,5.16)-2.58)**2)
                  TO GAUSSIAN
```

```
      SUBROUTINE FANCS (W,LW,AC,PERIOD)

      DIMENSION  W(1),AC(1)
      LOGICAL PERIOD
      IF (PERIOD) GO TO 300

      DO 200 I=1,LW
      TEMP=0.
      KEND=LW-I+1
        DO 100 J=1,KEND
100     TEMP=TEMP +W(J)*W(I+J-1)
200   AC(I)=TEMP
      AC(LW+1)=0.
      RETURN

300   LX=LW+1
      DO 500 IZ=1,LX
      IOFSET=IZ-1
      SUM=0.0
      DO 400 I=1,LW
400   SUM=SUM+W(I)*W(MOD(I+IOFSET-1,LW)+1)
500   AC(IZ) =SUM
      RETURN
      END
```

NOTES

STATEMENT "LOGICAL PERIOD" CORRESPONDS TO
PERIODIC OR APERIODIC CALCULATION OF THE ACF

```
      SUBROUTINE XFM (B,NPTS,LS)

      INTEGER*4 ITB(12)/12*0/
      REAL*4     RTB(28)/28*0.0/
      COMPLEX AX(3000),ACJX(3000),GAMN
      DIMENSION A(3000),ACJ(3000),AMPL(3000),X(3000),IWK(3000),B(1)
      EQUIVALENCE (AX(1),A(1)),(ACJX(1),ACJ(1))
      EQUIVALENCE (TITLE(1),RTB(5))
      REAL*8  TITLE(12)/' POWER SPECTRUM '/

      DO 10 I=1,NPTS
   10 A(I)=B(I)

C     CALCULATE THE FOURIER TRANSFORM AX

      CALL FFTR (A,GAMN,NPTS,IWK)
      NPHALF=NPTS/2

C     FORM THE CONJUGATE ACJX OF AX

      DO 1000 I=1,NPHALF
 1000 ACJX(I)=CONJG(AX(I))

C     CALCULATE THE P.SPECTRUM

      DO 2000  I=1,NPHALF
      RPART=REAL(AX(I)*ACJX(I))/FLOAT(NPTS)
      X(I)=FLOAT(I)-1.
 2000 AMPL(I)=SQRT(RPART)

C     PLOT THE P.SPECTRUM

      NPH1=NPHALF
      WRITE (6,3000) (X(I),AMPL(I),I=2,NPH1)
 3000 FORMAT (1X,F5.0,1X,F12.5)
      NPH1=NPH1-1
      CALL DRAWP (NPH1,X,AMPL(2),ITB,RTB)
      RETURN
      END
```

```
PERIOD=            TRUE
 1
 1
 1
-1
-1
 1
-1
            7           10          70

GRAPH HAS BEEN PLOTTED.
AUTO CORRELATIONS :
     0.        70.00000
     1.        62.00000
     2.        54.00000
     3.        46.00000
     4.        38.00000
     5.        30.00000
     6.        22.00000
     7.        14.00000
     8.         6.00000
     9.        -2.00000
    10.       -10.00000
    11.       -10.00000
    12.       -10.00000
    13.       -10.00000
    14.       -10.00000
    15.       -10.00000
    16.       -10.00000
    17.       -10.00000
    18.       -10.00000
    19.       -10.00000
    20.       -10.00000
    21.       -10.00000
    22.       -10.00000
    23.       -10.00000
    24.       -10.00000
    25.       -10.00000
    26.       -10.00000
    27.       -10.00000
    28.       -10.00000
    29.       -10.00000
    30.       -10.00000
    31.       -10.00000
    32.       -10.00000
    33.       -10.00000
    34.       -10.00000
    35.       -10.00000
    36.       -10.00000
    37.       -10.00000
    38.       -10.00000
    39.       -10.00000
    40.       -10.00000
    41.       -10.00000
    42.       -10.00000
    43.       -10.00000
    44.       -10.00000
    45.       -10.00000
    46.       -10.00000
    47.       -10.00000
    48.       -10.00000
    49.       -10.00000
    50.       -10.00000
    51.       -10.00000
    52.       -10.00000
    53.       -10.00000
```


Fig. 25. THE PRINTOUT OF THE COMPUTER PROGRAM #1 FOR THE UNSHAPED 7-BIT m-SEQUENCE.

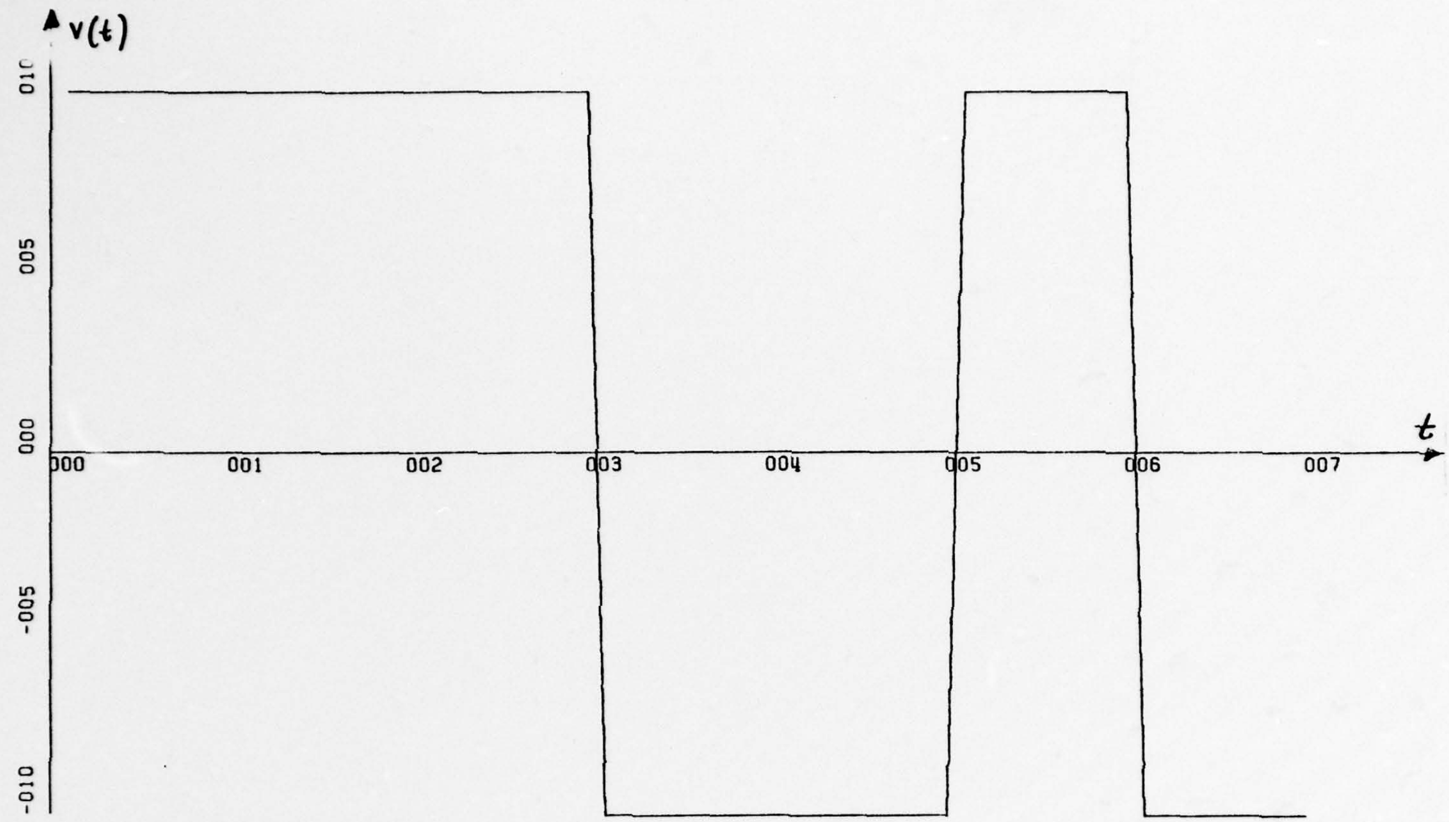
```
   54.        -10.00000
   55.        -10.00000
   56.        -10.00000
   57.        -10.00000
   58.        -10.00000
   59.        -10.00000
   60.        -10.00000
   61.         -2.00000
   62.          6.00000
   63.         14.00000
   64.         22.00000
   65.         30.00000
   66.         38.00000
   67.         46.00000
   68.         54.00000
   69.         62.00000

GRAPH HAS BEEN PLOTTED.
    1.         89.42333
    2.         72.73936
    3.         50.43881
    4.         28.50572
    5.         11.80389
    6.          2.54338
    7.          0.00003
    8.          1.45797
    9.          3.78377
   10.          4.82768
   11.          4.04735
   12.          2.22178
   13.          0.59311
   14.          0.00002
   15.          0.46305
   16.          1.35020
   17.          1.90305
   18.          1.73962
   19.          1.03060
   20.          0.29448
   21.          0.00001
   22.          0.25843
   23.          0.79311
   24.          1.17200
   25.          1.11961
   26.          0.69125
   27.          0.20536
   28.          0.00004
   29.          0.19372
   30.          0.61493
   31.          0.93878
   32.          0.92557
   33.          0.58928
   34.          0.18045

GRAPH TITLED
      POWER SPECTRUM

HAS BEEN PLOTTED.
```

Fig. 25. CONTINUED



X-SCALE=1.00E+01 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.

Fig. 26a. THE RECTANGULAR SHAPE 7-BIT m-SEQUENCE

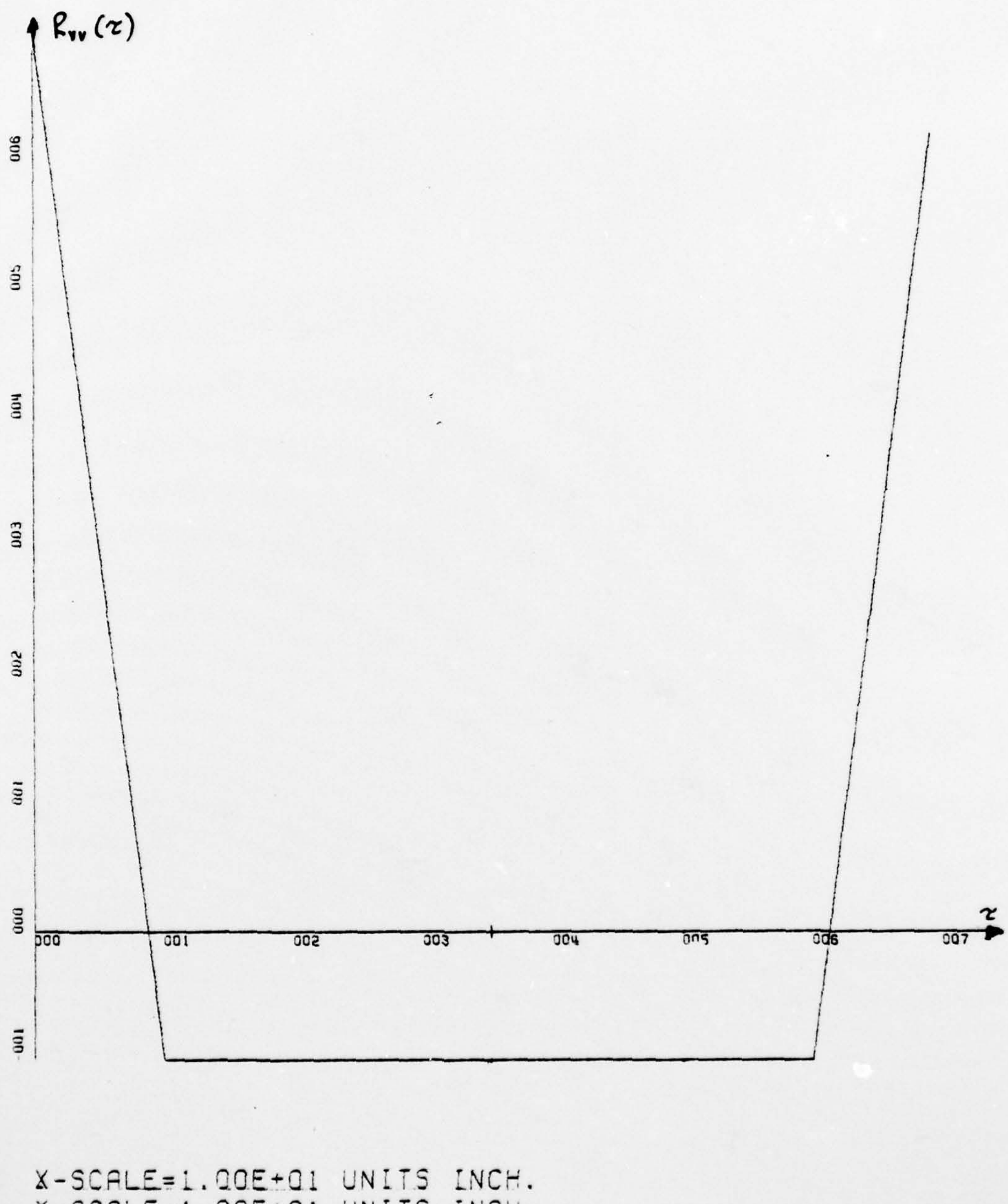
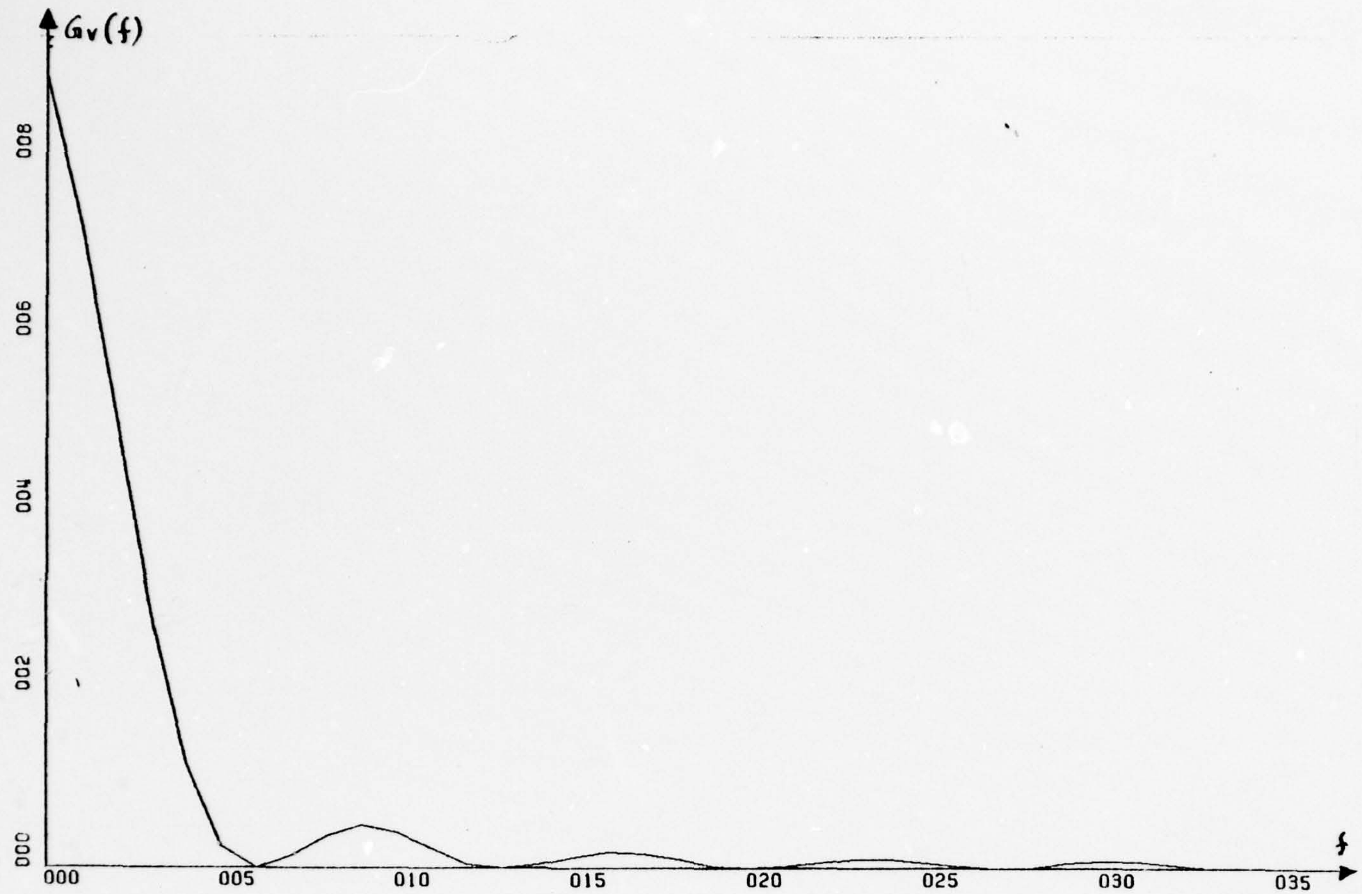


Fig. 26b. THE ACF OF THE RECTANGULAR SHAPE 7-BIT m-SEQUENCE.



X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E+01 UNITS INCH.

Fig. 26c. THE POWER SPECTRUM OF THE RECTANGULAR SHAPE 7-BIT m-SEQUENCE.

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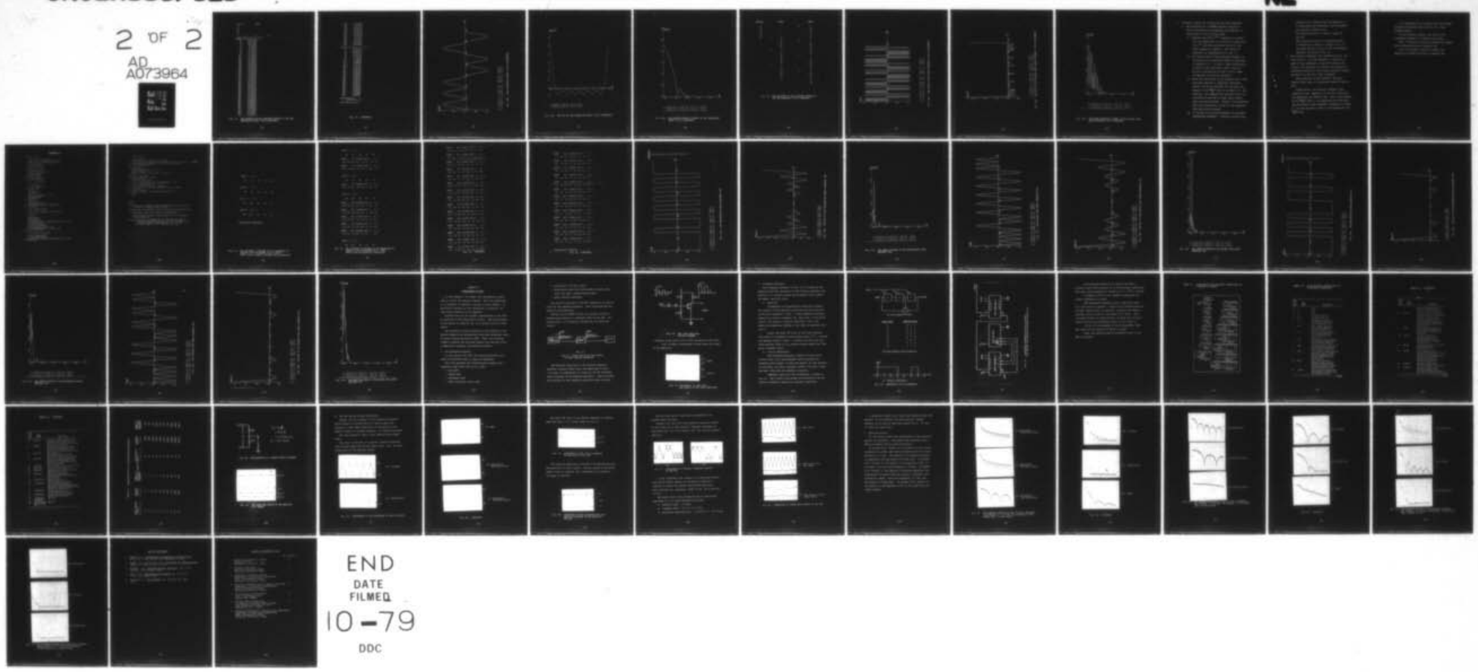

END
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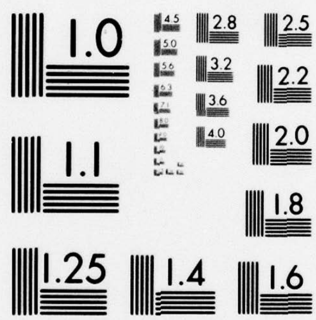


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

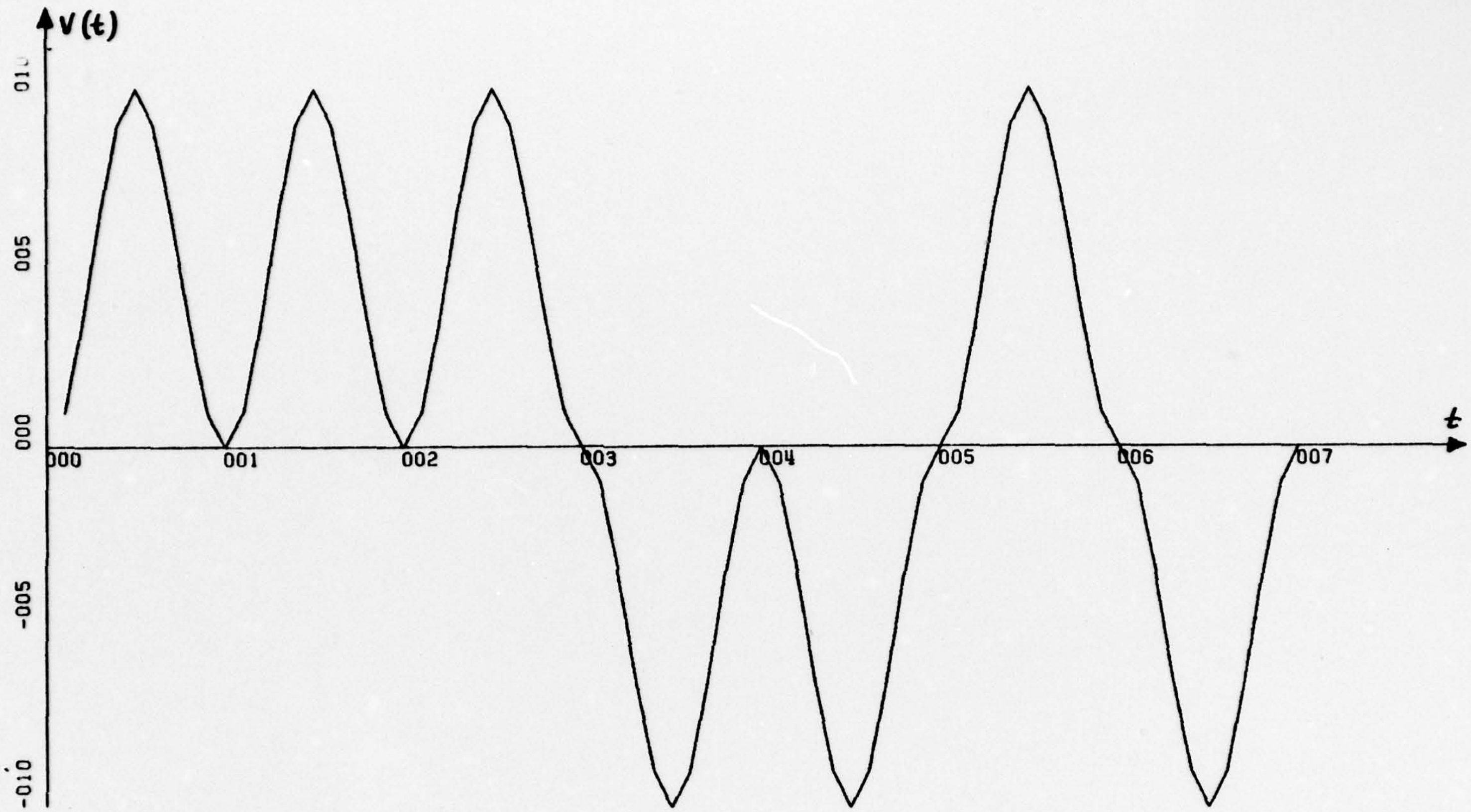
```
PERIOD=          TRUE
 1
  1
  1
 -1
 -1
  1
 -1
                7            10           70
GRAPH HAS BEEN PLOTTED.
AUTO CORRELATIONS :
      0.        26.24985
      1.        24.57875
      2.        20.13083
      3.        14.26823
      4.         8.46617
      5.         3.74997
      6.         0.46614
      7.        -1.58592
      8.        -2.81337
      9.        -3.51130
     10.        -3.75002
     11.        -3.51127
     12.        -2.88626
     13.        -2.11371
     14.        -1.48871
     15.        -1.24999
     16.        -1.48872
     17.        -2.11372
     18.        -2.88626
     19.        -3.51126
     20.        -3.74999
     21.        -3.51127
     22.        -2.88627
     23.        -2.11372
     24.        -1.48873
     25.        -1.24999
     26.        -1.48871
     27.        -2.11370
     28.        -2.88625
     29.        -3.51125
     30.        -3.74998
     31.        -3.51126
     32.        -2.88626
     33.        -2.11371
     34.        -1.48872
     35.        -1.24998
     36.        -1.48871
     37.        -2.11371
     38.        -2.88626
     39.        -3.51126
     40.        -3.74998
     41.        -3.51125
     42.        -2.88625
     43.        -2.11370
     44.        -1.48871
     45.        -1.24999
     46.        -1.48873
     47.        -2.11373
     48.        -2.88628
     49.        -3.51128
     50.        -3.75000
     51.        -3.51127
     52.        -2.88627
     53.        -2.11372
```

Fig. 27. THE PRINTOUT OF THE COMPUTER PROGRAM #1 FOR THE TRIANGULAR SHAPE 7-BIT m-SEQUENCE

```
      54.        -1.48872
      55.        -1.24998
      56.        -1.48870
      57.        -2.11370
      58.        -2.83624
      59.        -3.51126
      60.        -3.75000
      61.        -3.51129
      62.        -2.81335
      63.        -1.58590
      64.         0.46615
      65.         3.74997
      66.         8.46617
      67.        14.26823
      68.        20.13084
      69.        24.57875
```

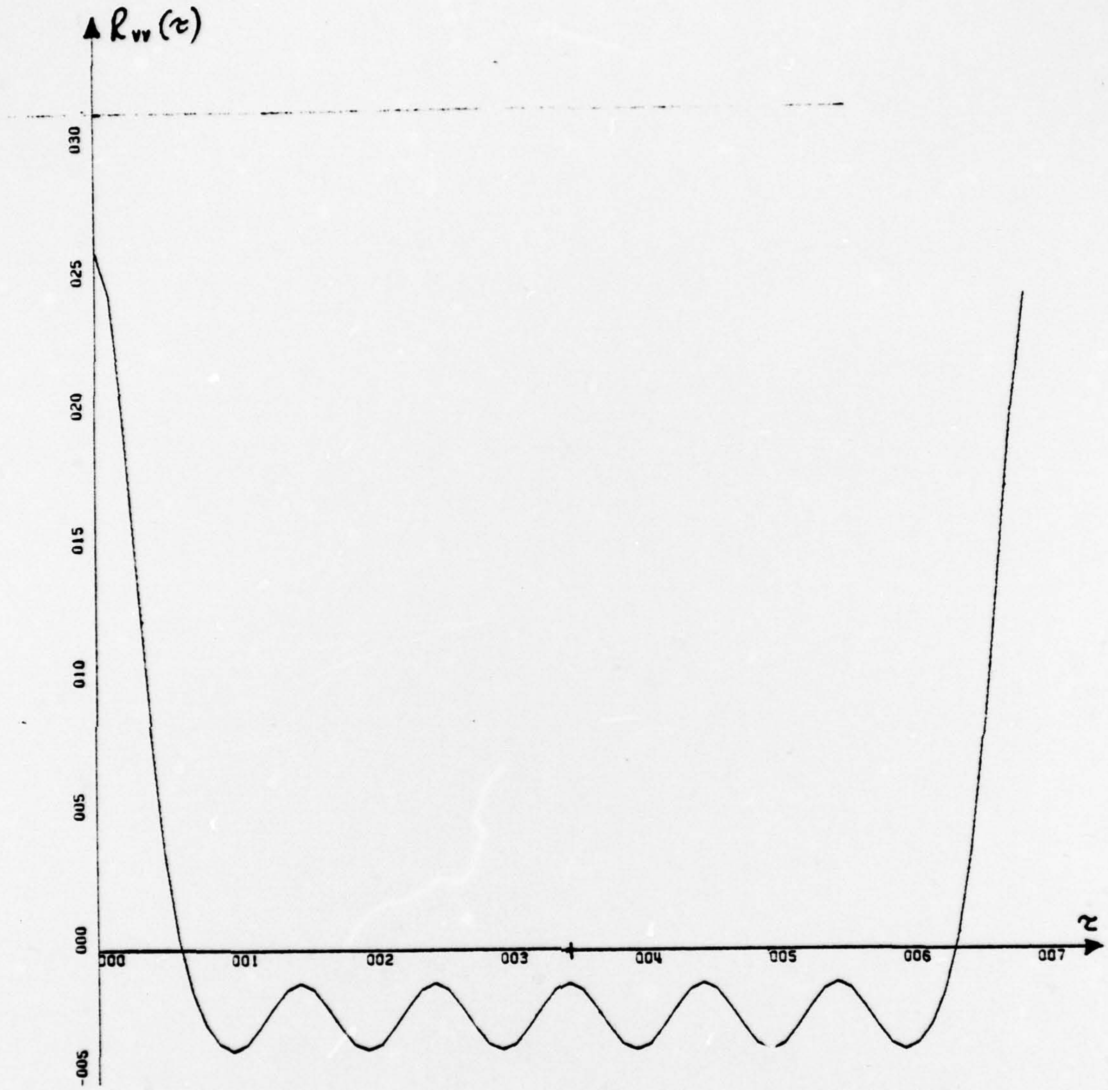
```
  GRAPH HAS BEEN PLOTTED.
       1.        23.28314
       2.        21.50557
       3.        18.81203
       4.        15.54861
       5.        12.09980
       6.         8.81940
       7.         0.74697
       8.         3.72312
       9.         2.09672
      10.         1.03815
      11.         0.42952
      12.         0.13291
      13.         0.02175
      14.         0.00002
      15.         0.00750
      16.         0.01534
      17.         0.01553
      18.         0.01040
      19.         0.00459
      20.         0.00099
      21.         0.00002
      22.         0.00050
      23.         0.00117
      24.         0.00131
      25.         0.00095
      26.         0.00044
      27.         0.00010
      28.         0.00001
      29.         0.00006
      30.         0.00009
      31.         0.00009
      32.         0.00006
      33.         0.00002
      34.         0.00002

  GRAPH TITLED
       POWER SPECTRUM

  HAS BEEN PLOTTED.
```

Fig. 27. CONTINUED.



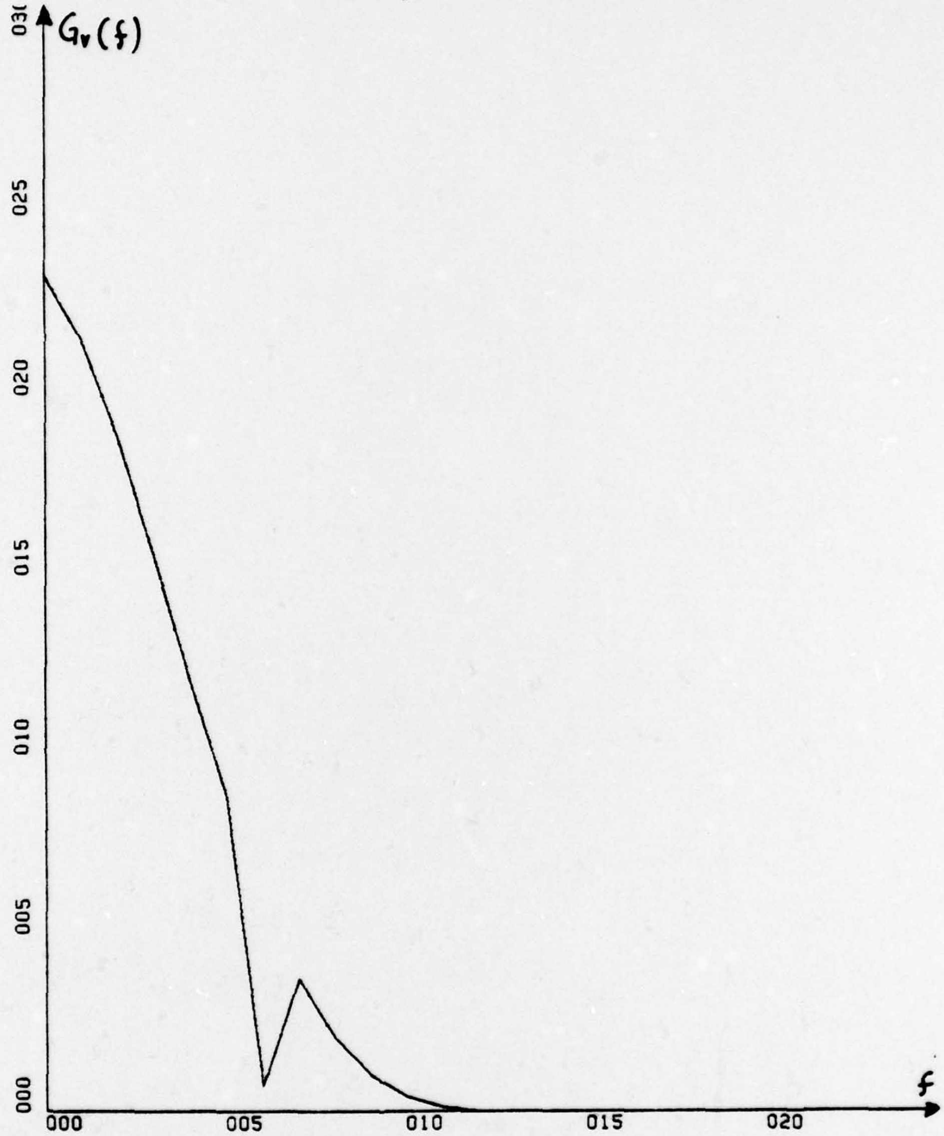
X-SCALE=1.00E+01 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.

Fig. 28a. THE TRIANGULAR SHAPE 7-BIT m-SEQUENCE.



X-SCALE=1.00E+01 UNITS INCH.
Y-SCALE=5.00E+00 UNITS INCH.

Fig. 28b. THE ACF OF THE TRIANGULAR SHAPE 7-BIT m-SEQUENCE.

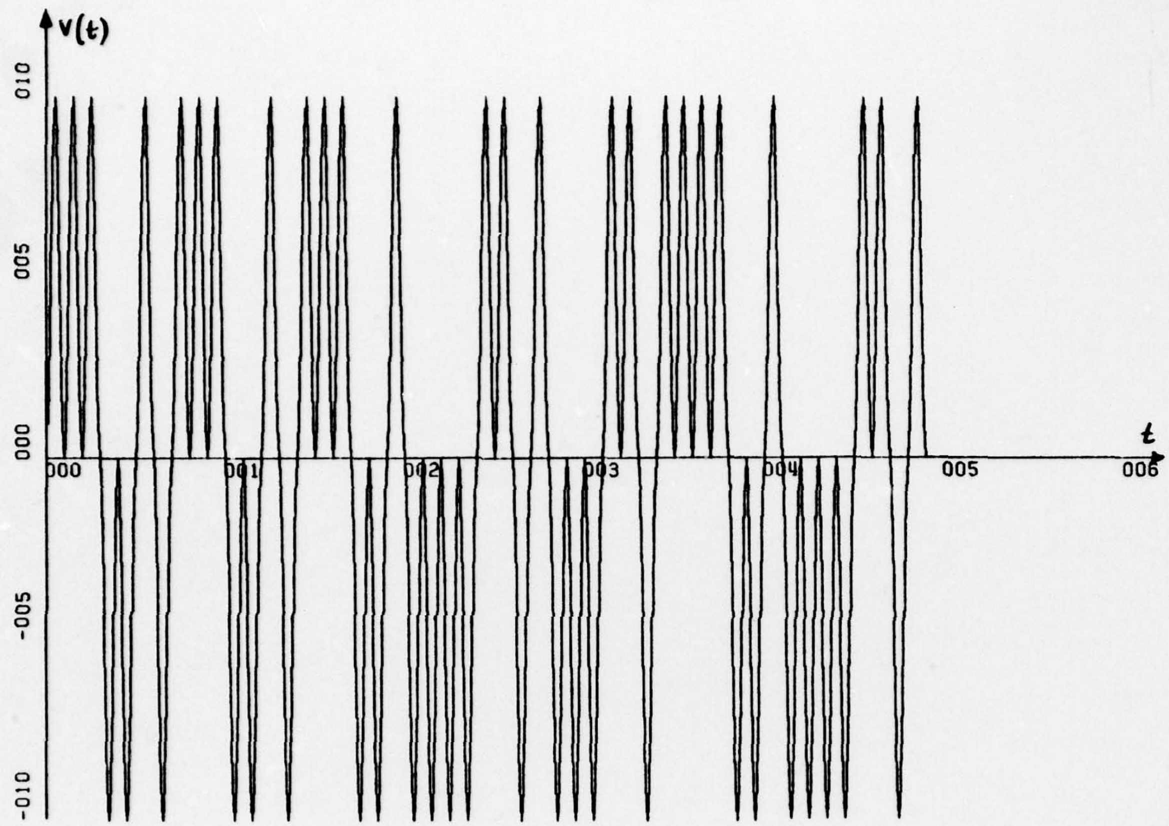


X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=5.00E+00 UNITS INCH.

Fig. 28c. THE POWER SPECTRUM (LINEAR) OF THE TRIANGULAR SHAPE 7-BIT m-SEQUENCE.

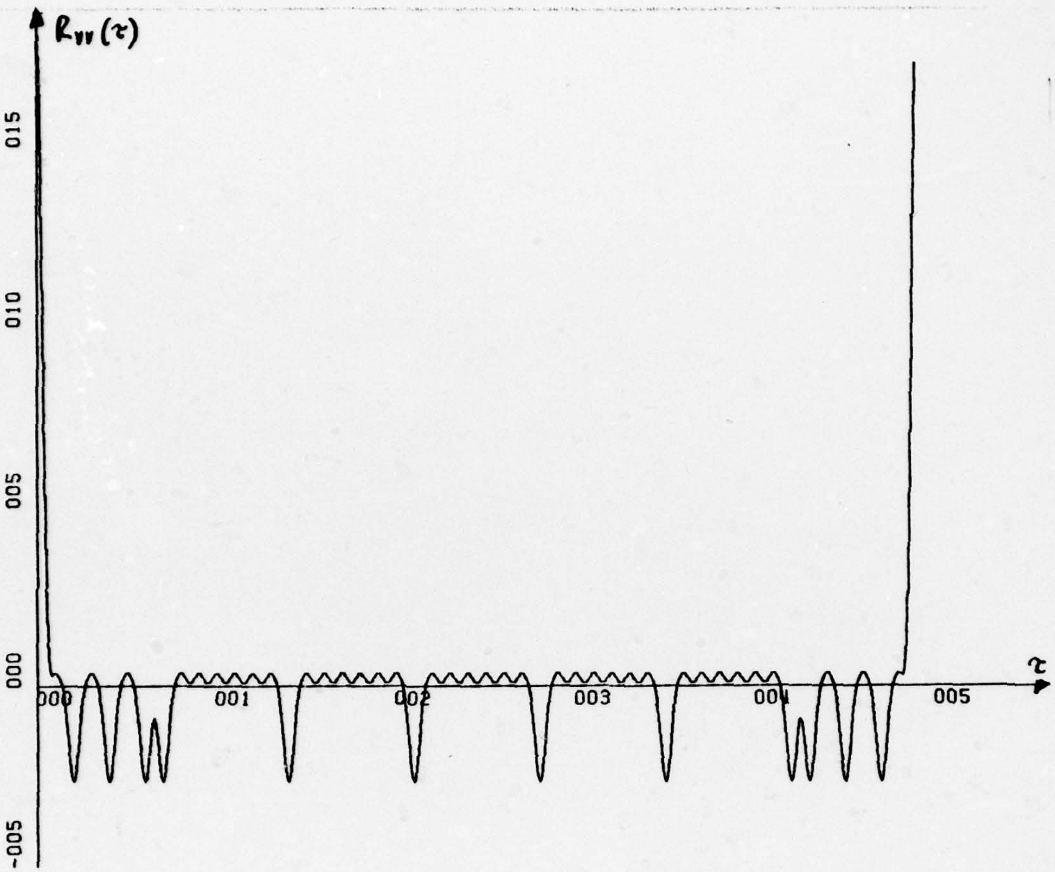
PERIOD=		TRUE		TRUE
1			-1	
1				-1
1				-1
-1				-1
-1				1
1				1
-1	1	1		-1
		1		1
		1	-1	
		-1		-1
		-1		-1
		1		-1
		-1		1
	1			1
		1		-1
		1		1
		1	1	
		-1		1
		-1		1
		1		1
		-1		-1
	1			-1
		1		1
		1		-1
		1	-1	
		-1		-1
		-1		-1
		1		-1
		-1		1
				1
				-1
				1

Fig. 29. THE PRINTOUT OF THE COMPUTER PROGRAM #1 FOR THE EXTENDED 7-BIT m-SEQUENCE.



X-SCALE=1.00E+02 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.

Fig. 30a. THE RAISED SINE SHAPE EXTENDED 7-BIT m-SEQUENCE.



X-SCALE=1.00E+02 UNITS INCH.
Y-SCALE=5.00E+01 UNITS INCH.

Fig. 30b. THE ACF OF THE RAISED SINE SHAPE EXTENDED 7-BIT m-SEQUENCE.

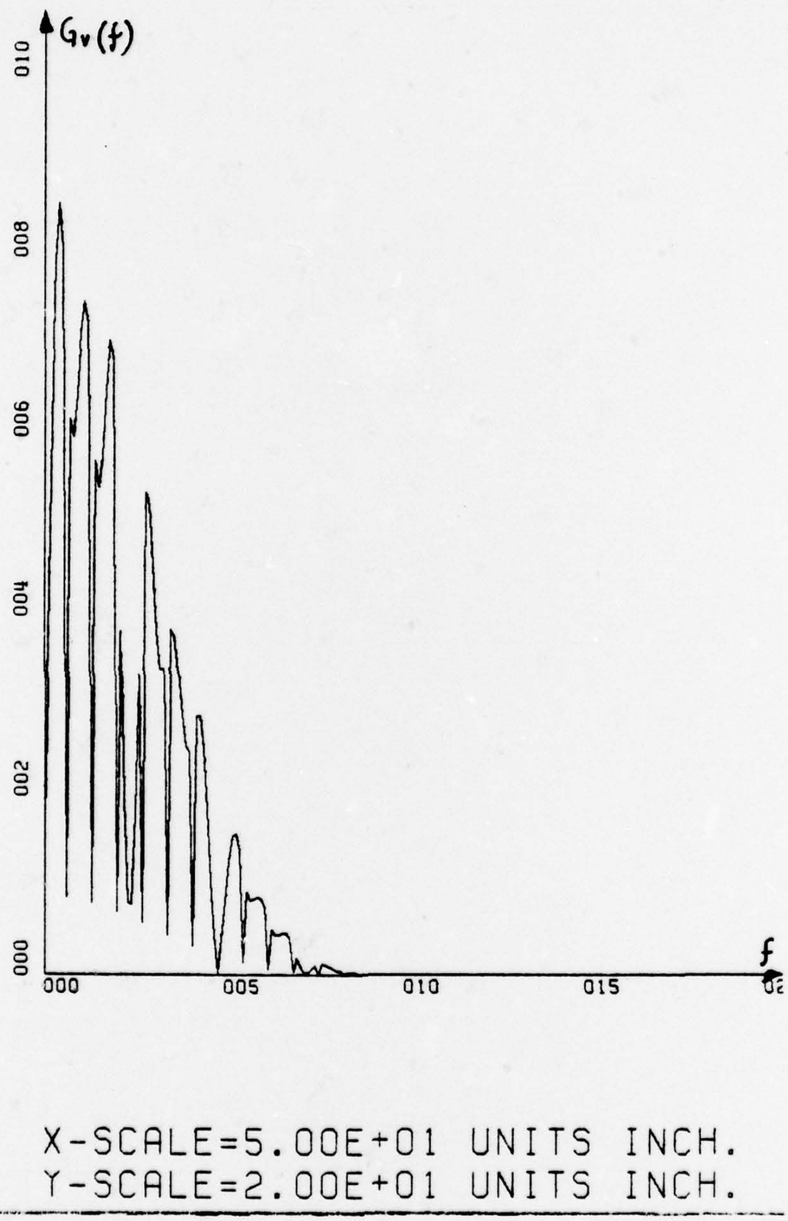


Fig. 30c. THE POWER SPECTRUM (LINEAR) OF THE RAISED SINE SHAPE EXTENDED 7-BIT m-SEQUENCE.

2. Program to search for interesting arbitrary sequences.

   a. The algorithm for a FORTRAN computer program by which interesting non m-sequences are examined, is constructed in the following steps.

      (1) Generate the first $2^{(L-1)}$ sequences of length n. This is accomplished by counting in binary from 0 to 2^{L-1} and thus generating the first half binary numbers of length L. The resulting sequences are represented with 1 and -1.

      (2) The periodic ACF of each generated sequence is calculated using subroutine PANOS (as described in Appendix A.1). In fact, a small modification is made in this subroutine, which gives the option of calculating the ACF's of any number of sequences as they are generated.

      (3) After the calculation of the periodic ACF of each generated sequence is completed, sufficient control points are provided, so that ACF's not similar to the $\frac{\sin x}{x}$ form are filtered out. The remaining are compared for similarity with the the previous ones and the same (which repeat) ACF's are also filtered. Finally, the interesting ACF's are printed out, as well as the sequences from which they originate.

      (4) At the end of the program appears the statement CALCULATION COMPLETED. A printout without that

statement will indicate that the computation is interrupted and unfinished, having exceeded the available computer time.

The computer program is shown on pages 108 and 109.

The resulting printout of interesting ACF's of sequences of length 8 is shown in Fig. 31.

The above results as well as the corresponding sequences are shown in Fig. 32.

b. The resulting sequences with interesting ACF's for every length L are then examined. A decision is made for the usefulness of each individually and finally, the sequences of interest are punched and processed according to the already discussed computer procedure for the main linear sequences.

Their spectrum is then examined, and pulse shaping takes place to investigate possible improvement.

Unfortunately, the required extremely large computation time appears to be the main factor for not approaching the desired form. Due to the geometry of the $\frac{\sin x}{x}$ curve, it is understood that much more than 20 points of ACF (onesided) [sequences of length L = 20] are required to form a curve approaching the $\frac{\sin x}{x}$ form.

It is suggested that a project using the already constructed programs could be used, for a more extended search.

In the following figures, the plots of two interesting sequences of length 20 are shown.

Figs. 33 through 34 show the unshaped and shaped with raised-sine plots of sequence 20B.

Figs. 35 through 36 show the unshaped and shaped with raised-sine plots of sequence 20X.

PROGRAM #2

```
DECLARATIONS

      INTEGER CODE (10000)
      REAL RCODE (10000),AC (10001)
      DIMENSION AAUTO (21,400)
      LOGICAL LONG
      DO 3 I3=1,21
    3 AAUTO (I3,1)=0.
      NAUTO=1
      READ (5,4) LONG
    4 FORMAT (L10)
      READ (5,5) PERIOD
    5 FORMAT (L10)
      READ (5,10) L
   10 FORMAT (I2)
      READ (5,15) X
   15 FORMAT (F10.0)

C     CODE GENERATION

      NN=2**(L-1)
      DO 100 II=1,NN
      DO 20 I=1,L
   20 CODE(I)=0
      NI=II-1
      DO 30 M=1,L
      JJ=L-M
      IF(NI.LT.2**JJ) GO TO 30
      CODE (JJ+1)=1
      NI=NI-2**JJ
   30 CONTINUE
      N=L+1
      DO 50 I=1,L
      RCODE(I)=CODE(I)
      IF(CODE(I).EQ.0) RCODE(I)=-1.
   50 CONTINUE

C     AUTO CORRELATIONS

      CALL PANOS (RCODE,L,AC,PERIOD)

C     BOUNDS

      NHALF=N/2
      NHPI=NHALF+1
      FLPFLP=-1.
      IF (ABS(AC(2)).GT.X*FLOAT(L)) GO TO 100
      SECOND=-AC(2)
      DO 70 I7=2,NHALF
      TEMP=FLPFLP*AC(I7)
      IF(TEMP.LT.0) GO TO 100
      IF (TEMP.GT.SECOND) GO TO 100
   70 FLPFLP=-FLPFLP

C     ELIMINATE SAME AUTOS

      DO 73 I73=1,NAUTO
      DO 72 I72=1,NHPI
      IF(AC(I72).NE.AAUTO(I72,I73)) GO TO 73
   72 CONTINUE
```

```
C       WRITE CODES
        I73M1=I73-1
        IF (LONG) WRITE (6,97) II,I73M1
   97 FORMAT (//,' CODE( ',I5,' ) GIVES AUTO ( ',I3, ' ) : ',//)
        IF(LONG) WRITE (6,85) (RCODE(N-IDL),IDL=1,L)
   85 FORMAT (1X,30F4.0)
        GO TO 100
   73 CONTINUE
        NAUTO=NAUTO+1
        IF(NAUTO.LE.400) GO TO 87
        WRITE (6,86)
   86 FORMAT (' TOO MANY AUTOS : STOP ')
        STOP
   87 DO 88 I=1,NHPI
   88 AAUTO(I,NAUTO)= AC(I)
        NAM1=NAUTO-1
        WRITE (6,90) NAM1
   90 FORMAT (////,1X,' AUTO ( ',I3,' ) : ',//)
        WRITE (6,95) (AC(IDL),IDL=1,NHPI)
   95 FORMAT (1X,20F6.0)
        IF(LONG) WRITE (6,97) II,NAM1
        IF(LONG) WRITE (6,85) (RCODE(N-IDL),IDL=1,L)
  100 CONTINUE
        WRITE (6,200)
  200 FORMAT (/////,' CALCULATION COMPLETED ')
        STOP
        END
```

```
NOTES
-------

LONG=TRUE FOR  WRITING CODES CORRESPONDING TO EACH ACF
     FAULSE FOR WRITING ONLY ACF,S

PERIOD=TRUE FOR PERIODIC ACF,OR FAULSE FOR APERIODIC ACF

   L=DESIRED LENGTH OF CODES TO BE EXAMINED

   X=PERCENTAGE OF ACF,S MAIN LOBE,NOT TO BE EXCEEDED
     BY SECONDARIES

BOUNDS:EVERY ACF IS EXAMINED FOR ALTERNATING VALUES.
       THEN,THE SECONDARY LOBES  MUST NOT EXCEED
       A PREDETERMINED PERCENTAGE (X) OF THE MAIN LOBE.
       IN MOST CASES OF THIS SEARCH X WAS 0.5
```

```
AUTO (   1 ) :

   8.     0.     0.     0.    -4.

AUTO (   2 ) :

   8.     0.     0.     0.     8.

AUTO (   3 ) :

   8.    -4.     4.    -4.     4.

AUTO (   4 ) :

   8.    -4.     0.     0.     0.

CALCULATION COMPLETED
```

Fig. 31. THE PRINTOUT OF PROGRAM #2 FOR SEQUENCES OF LENGTH 8 WITH STATEMENT LONG = FALSE. (ACF's only, without corresponding sequences)

```
AUTO (   1 ) :

   8.    0.    0.    0.   -4.

CODE(    12 ) GIVES AUTO (    1 ) :
 -1. -1. -1. -1.  1. -1.  1.  1.

CODE(    14 ) GIVES AUTO (    1 ) :
 -1. -1. -1. -1.  1.  1. -1.  1.


AUTO (   2 ) :

   8.    0.    0.    0.    8.

CODE(    18 ) GIVES AUTO (    2 ) :
 -1. -1. -1.  1. -1. -1. -1.  1.


AUTO (   3 ) :

   8.   -4.    4.   -4.    4.

CODE(    22 ) GIVES AUTO (    3 ) :
 -1. -1. -1.  1. -1.  1. -1.  1.

CODE(    23 ) GIVES AUTO (    1 ) :
 -1. -1. -1.  1. -1.  1.  1. -1.

CODE(    27 ) GIVES AUTO (    1 ) :
 -1. -1. -1.  1.  1. -1.  1. -1.

CODE(    35 ) GIVES AUTO (    2 ) :
 -1. -1.  1. -1. -1. -1.  1. -1.

CODE(    43 ) GIVES AUTO (    3 ) :
 -1. -1.  1. -1.  1. -1.  1. -1.


AUTO (   4 ) :

   8.   -4.    0.    0.    0.
```

Fig. 32. THE PRINTOUT OF PROGRAM #2 FOR SEQUENCES OF LENGTH 8 WITH STATEMENT LONG = TRUE. (ACF's and corresponding sequences).

```
CODE(    44 ) GIVES ALTC (   4 ) :
 -1. -1.  1. -1.  1. -1.  1.  1.

CODE(    45 ) GIVES ALTC (   1 ) :
 -1. -1.  1. -1.  1.  1. -1. -1.

CODE(    48 ) GIVES ALTC (   1 ) :
 -1. -1.  1. -1.  1.  1.  1.  1.

CODE(    53 ) GIVES ALTC (   1 ) :
 -1. -1.  1.  1. -1.  1. -1. -1.

CODE(    54 ) GIVES ALTC (   4 ) :
 -1. -1.  1.  1. -1.  1. -1.  1.

CODE(    62 ) GIVES ALTC (   1 ) :
 -1. -1.  1.  1.  1.  1. -1.  1.

CODE(    68 ) GIVES ALTC (   1 ) :
 -1.  1. -1. -1. -1. -1.  1.  1.

CODE(    69 ) GIVES ALTC (   2 ) :
 -1.  1. -1. -1. -1.  1. -1. -1.

CODE(    70 ) GIVES ALTC (   3 ) :
 -1. -1. -1. -1. -1.  1. -1.  1.

CODE(    78 ) GIVES ALTC (   4 ) :
 -1.  1. -1. -1.  1.  1. -1.  1.

CODE(    80 ) GIVES ALTC (   1 ) :
 -1.  1. -1. -1.  1.  1.  1.  1.

CODE(    82 ) GIVES ALTC (   3 ) :
 -1.  1. -1.  1. -1. -1. -1.  1.

CODE(    84 ) GIVES ALTC (   4 ) :
 -1.  1. -1.  1. -1. -1.  1.  1.

CODE(    85 ) GIVES ALTC (   3 ) :
 -1.  1. -1.  1. -1.  1. -1. -1.

CODE(    87 ) GIVES ALTC (   4 ) :
 -1.  1. -1.  1. -1.  1.  1. -1.
```

Fig. 32. CONTINUED

```
CODE(     88 ) GIVES AUTC (    3 ) :
 -1.  1. -1.  1. -1.  1.  1.  1.

CODE(     89 ) GIVES AUTC (    1 ) :
 -1.  1. -1.  1.  1. -1. -1. -1.

CODE(     90 ) GIVES AUTC (    4 ) :
 -1.  1. -1.  1.  1. -1. -1.  1.

CODE(     94 ) GIVES AUTC (    3 ) :
 -1.  1. -1.  1.  1.  1. -1.  1.

CODE(     95 ) GIVES AUTC (    1 ) :
 -1.  1. -1.  1.  1.  1.  1. -1.

CODE(     98 ) GIVES AUTC (    1 ) :
 -1.  1.  1. -1. -1. -1. -1.  1.

CODE(    102 ) GIVES AUTC (    4 ) :
 -1.  1.  1. -1. -1.  1. -1.  1.

CODE(    105 ) GIVES AUTC (    1 ) :
 -1.  1.  1. -1.  1. -1. -1. -1.

CODE(    107 ) GIVES AUTC (    4 ) :
 -1.  1.  1. -1.  1. -1.  1. -1.

CODE(    118 ) GIVES AUTC (    3 ) :
 -1.  1.  1.  1. -1.  1. -1.  1.

CODE(    120 ) GIVES AUTC (    2 ) :
 -1.  1.  1.  1. -1.  1.  1.  1.

CODE(    122 ) GIVES AUTC (    1 ) :
 -1.  1.  1.  1.  1. -1. -1.  1.

CODE(    123 ) GIVES AUTC (    1 ) :
 -1.  1.  1.  1.  1. -1.  1. -1.


CALCULATICN CCMPLETEC
```

Fig. 32. CONTINUED

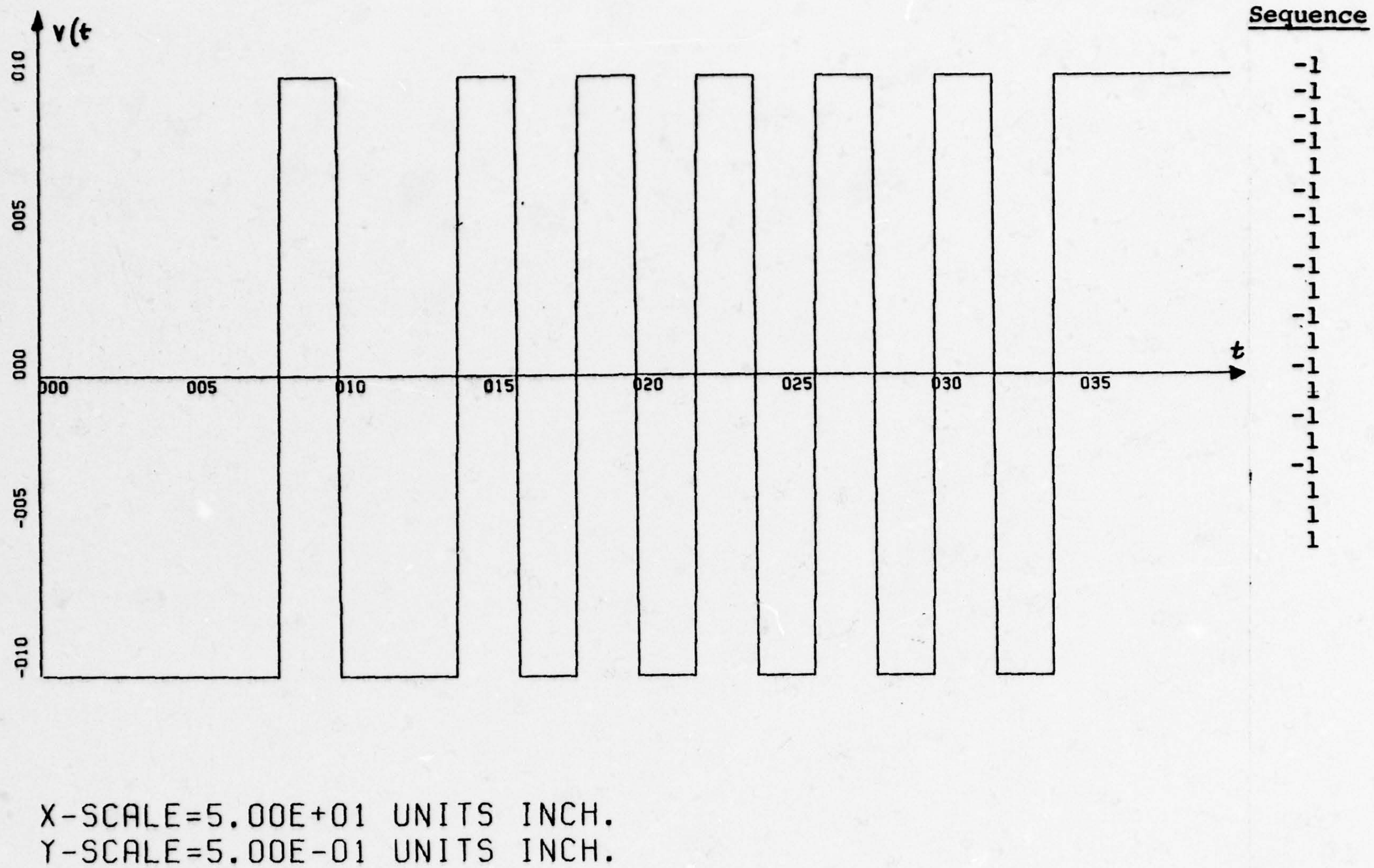
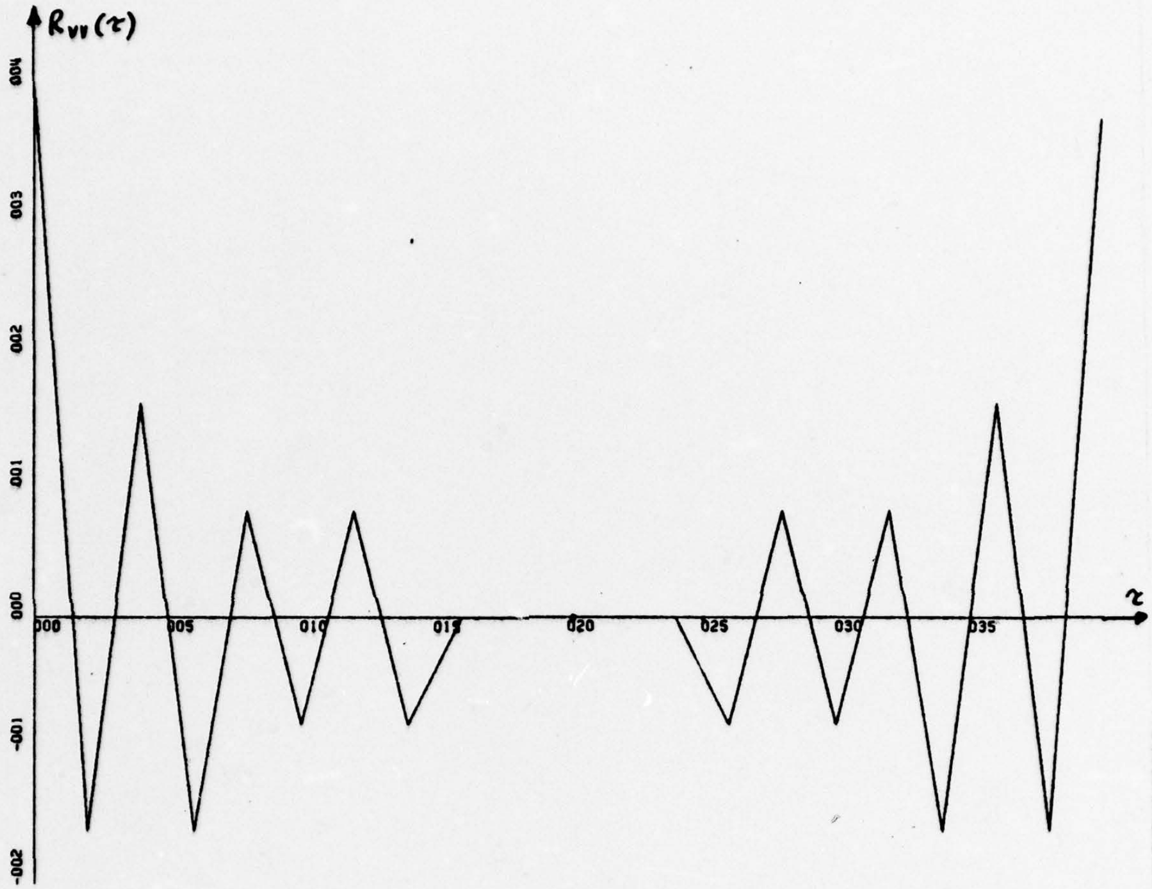


Fig. 33a. THE RECTANGULAR SHAPE SEQUENCE 20B.



X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=1.00E+02 UNITS INCH.

Fig. 33b. THE ACF OF THE RECTANGULAR SHAPE SEQUENCE 20B.

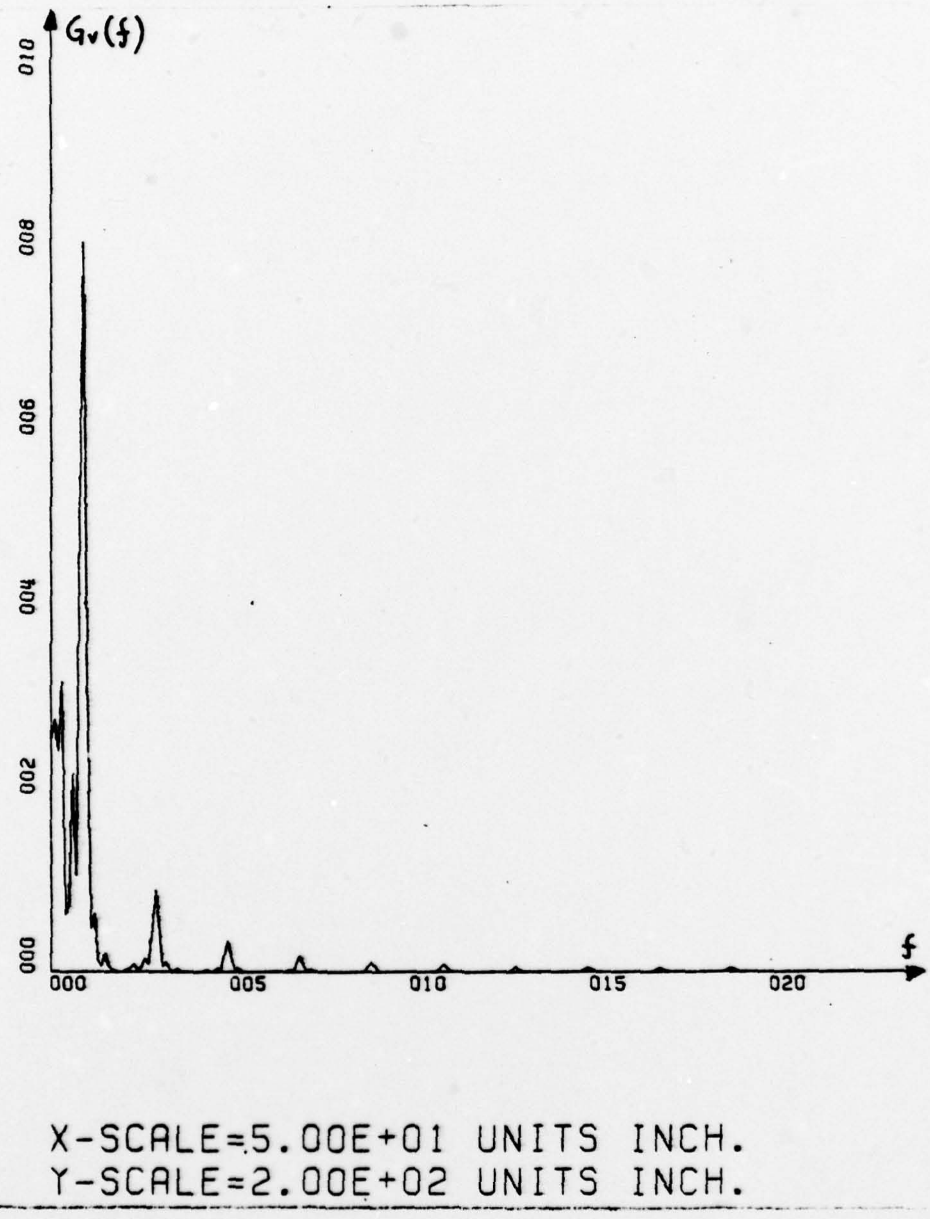
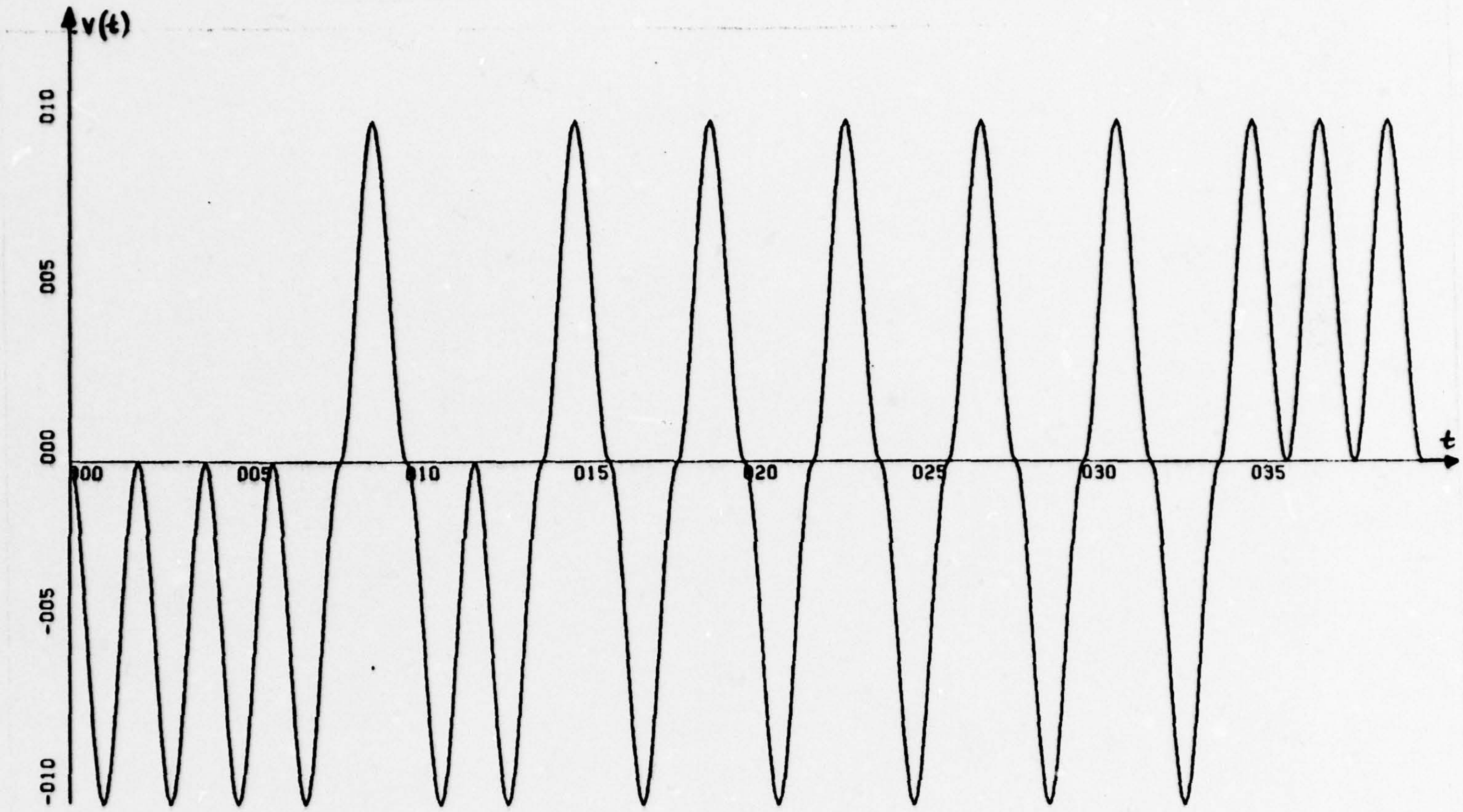
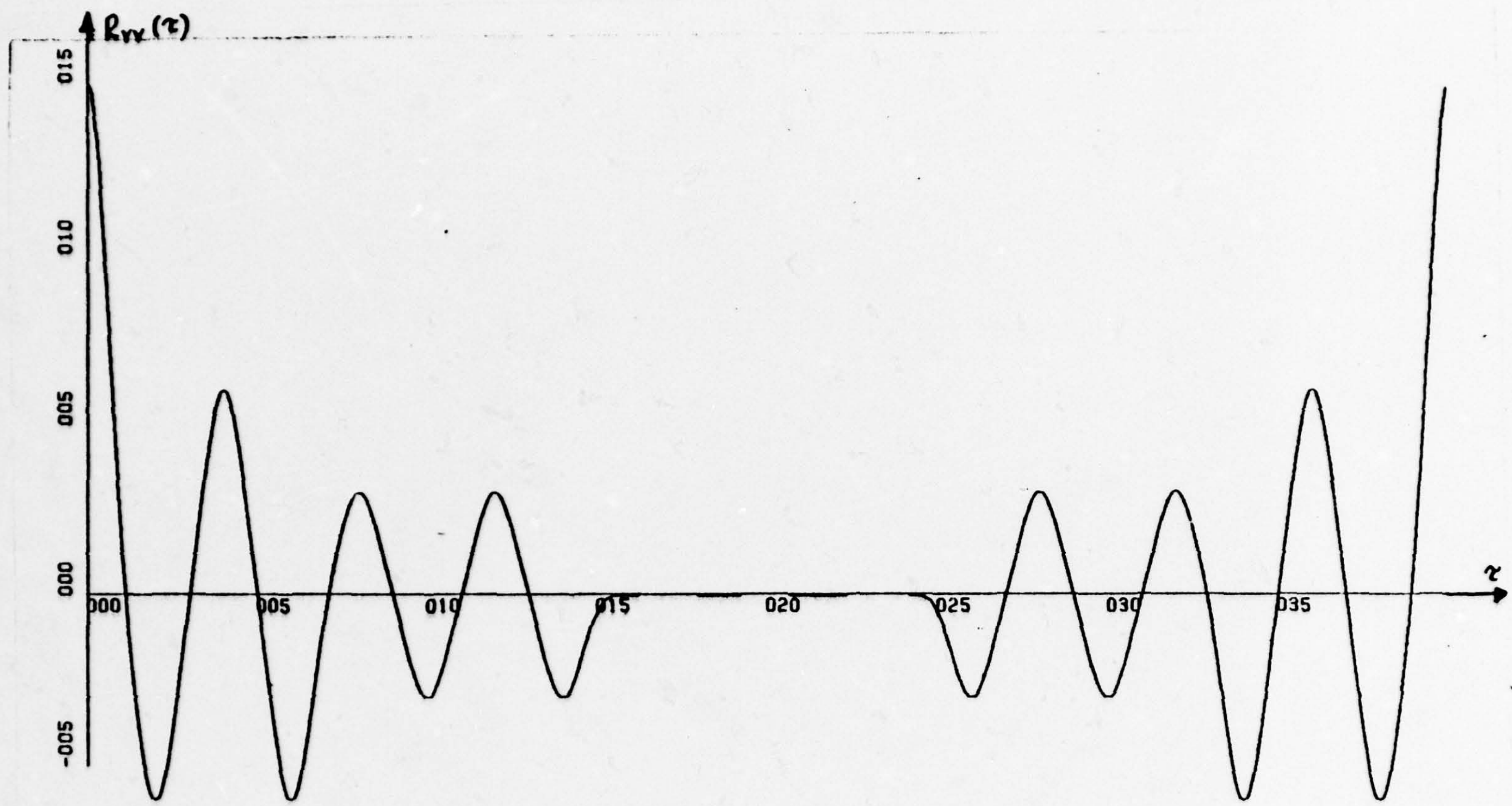


Fig. 33c. THE POWER SPECTRUM OF THE RECTANGULAR SHAPE SEQUENCE 20B.



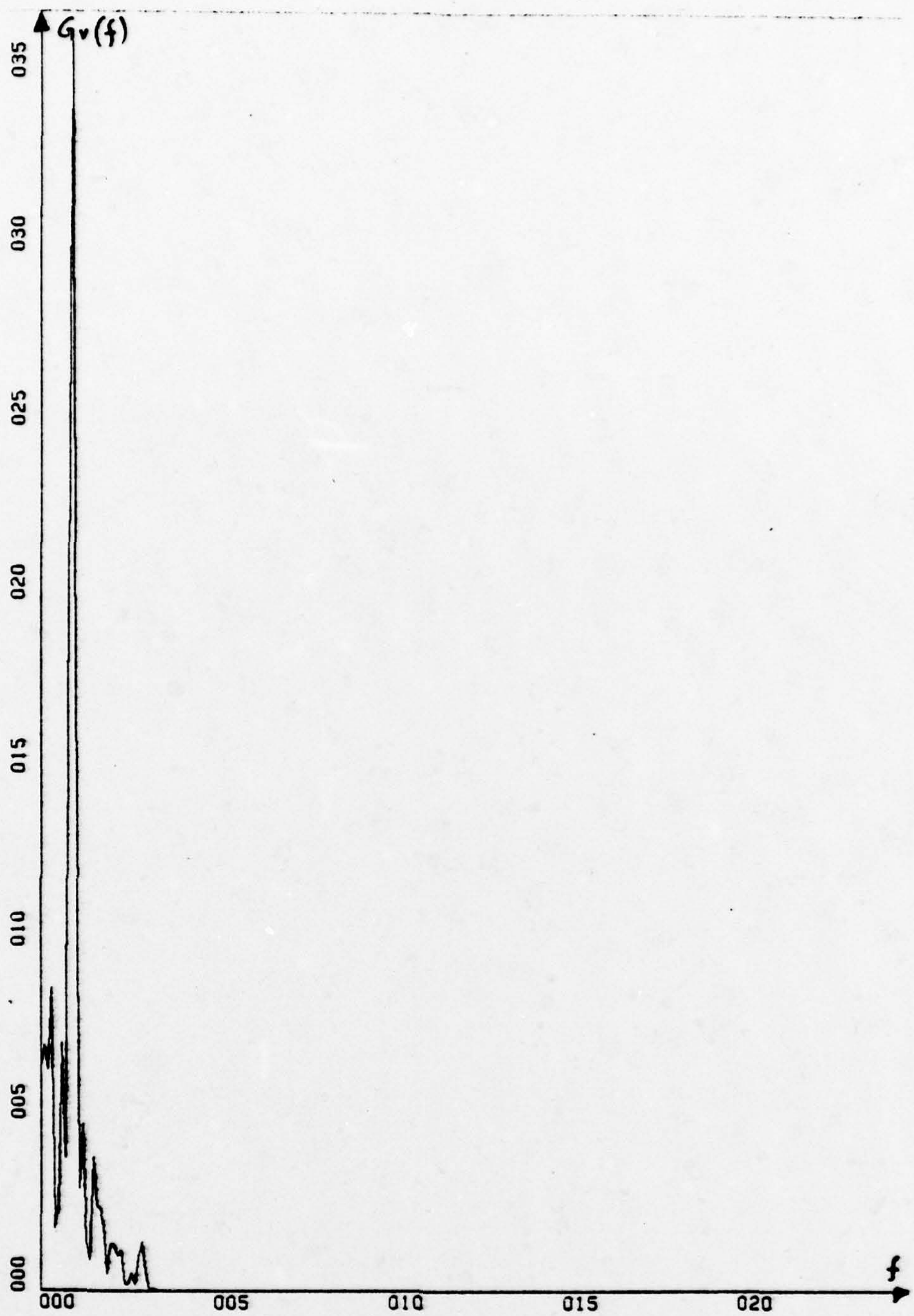
X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.

Fig. 34a. THE RAISED SINE SHAPE SEQUENCE 20B.



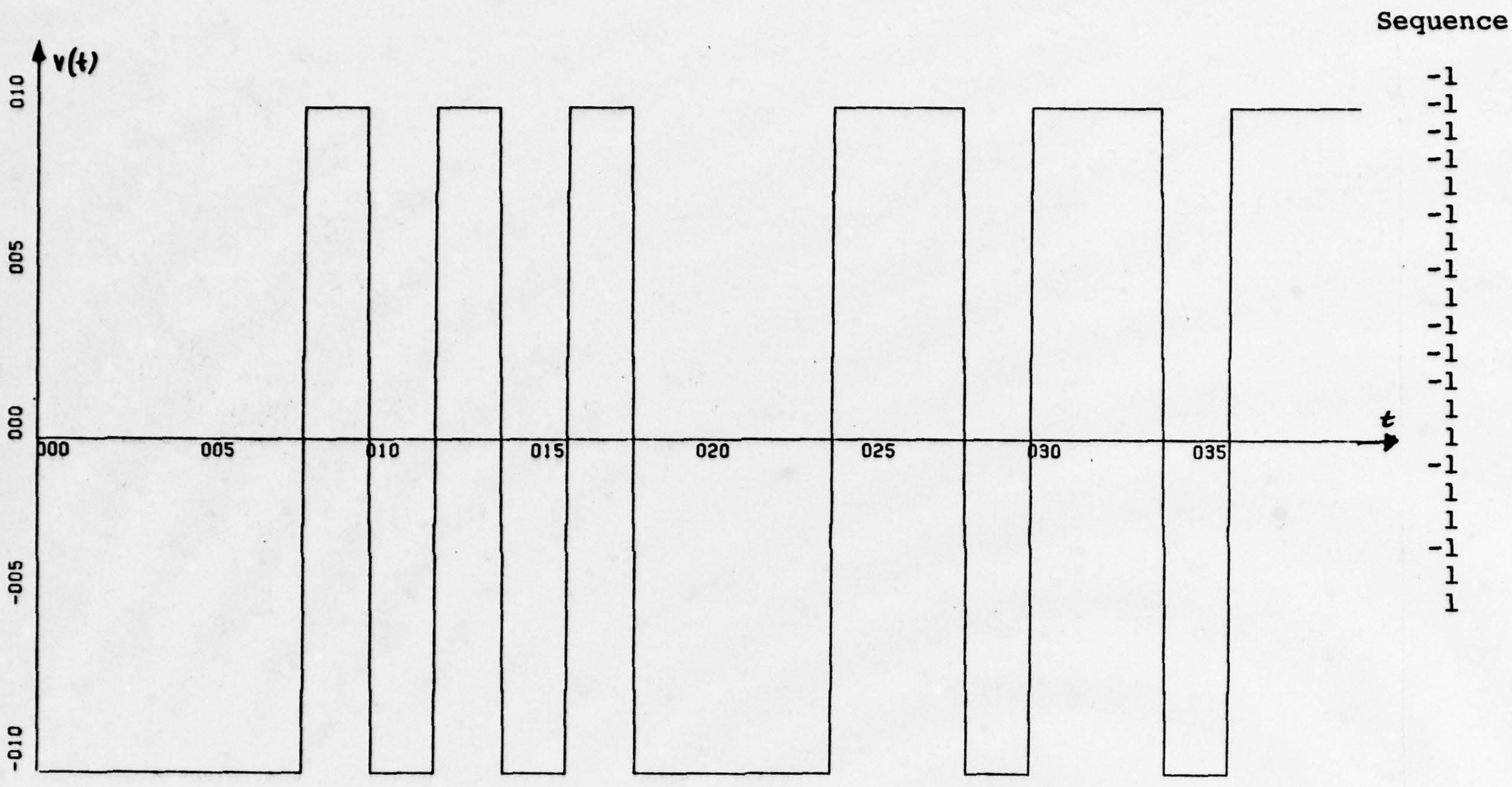
X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E+01 UNITS INCH.

Fig. 34b. THE ACF OF THE RAISED SINE SHAPE SEQUENCE 20B.



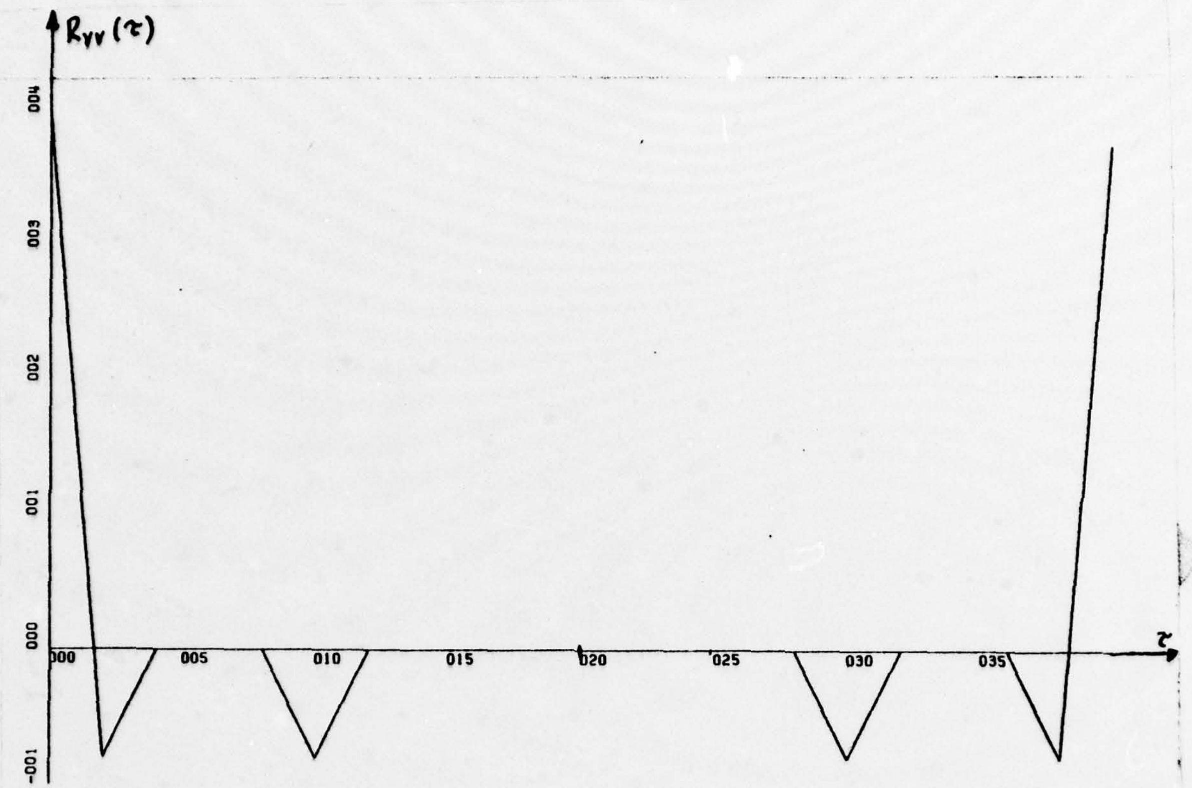
X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E+01 UNITS INCH.

Fig. 34c. THE POWER SPECTRUM OF THE RAISED SINE SHAPE SEQUENCE 20B.



X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.

Fig. 35a. THE RECTANGULAR SHAPE SEQUENCE 20X.

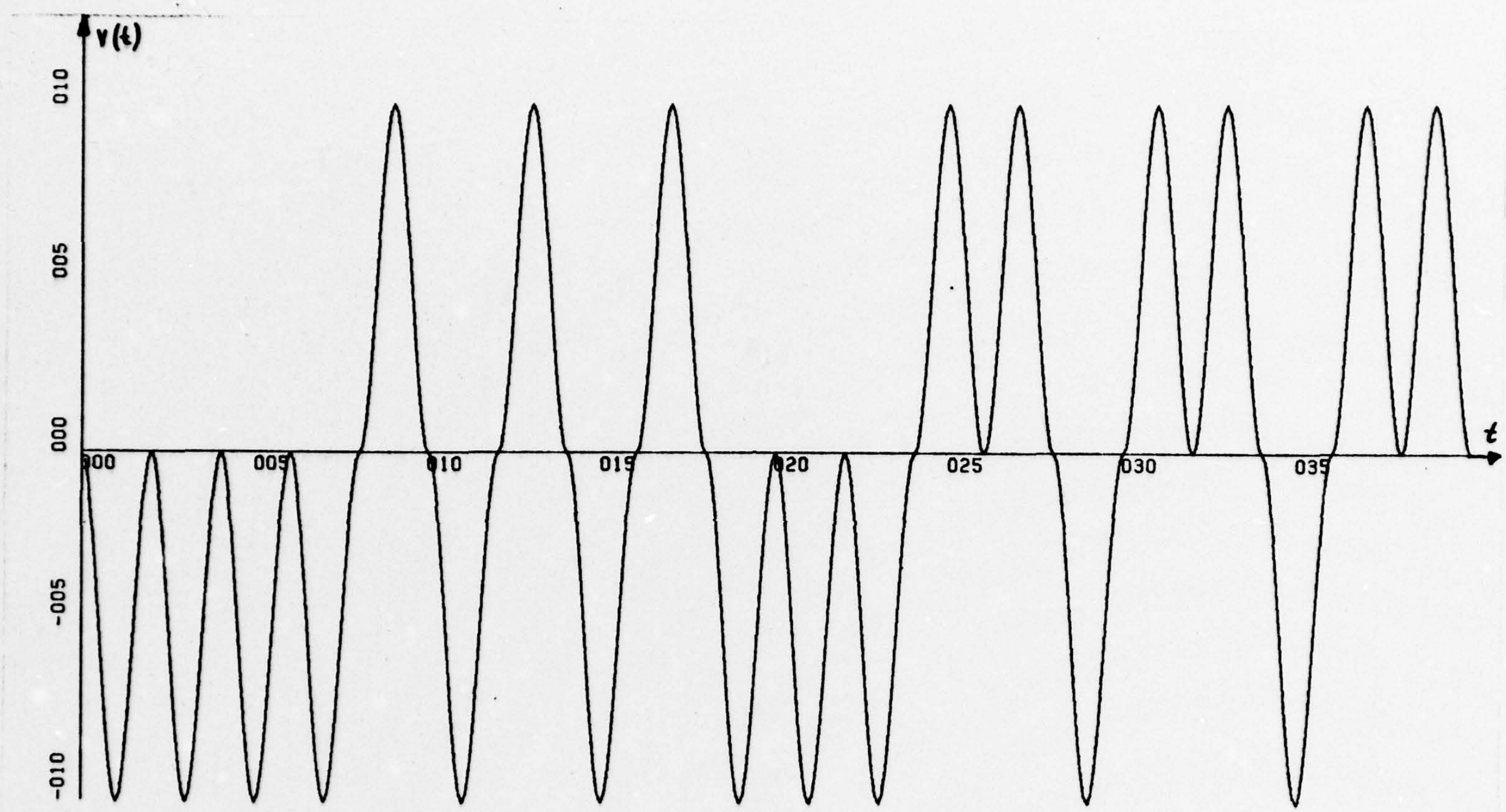


X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=1.00E+02 UNITS INCH.

Fig. 35b. THE ACF OF THE RECTANGULAR SHAPE SEQUENCE 20X.

X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=1.00E+02 UNITS INCH.

Fig. 35c. THE POWER SPECTRUM OF THE RECTANGULAR SHAPE SEQUENCE 20X.

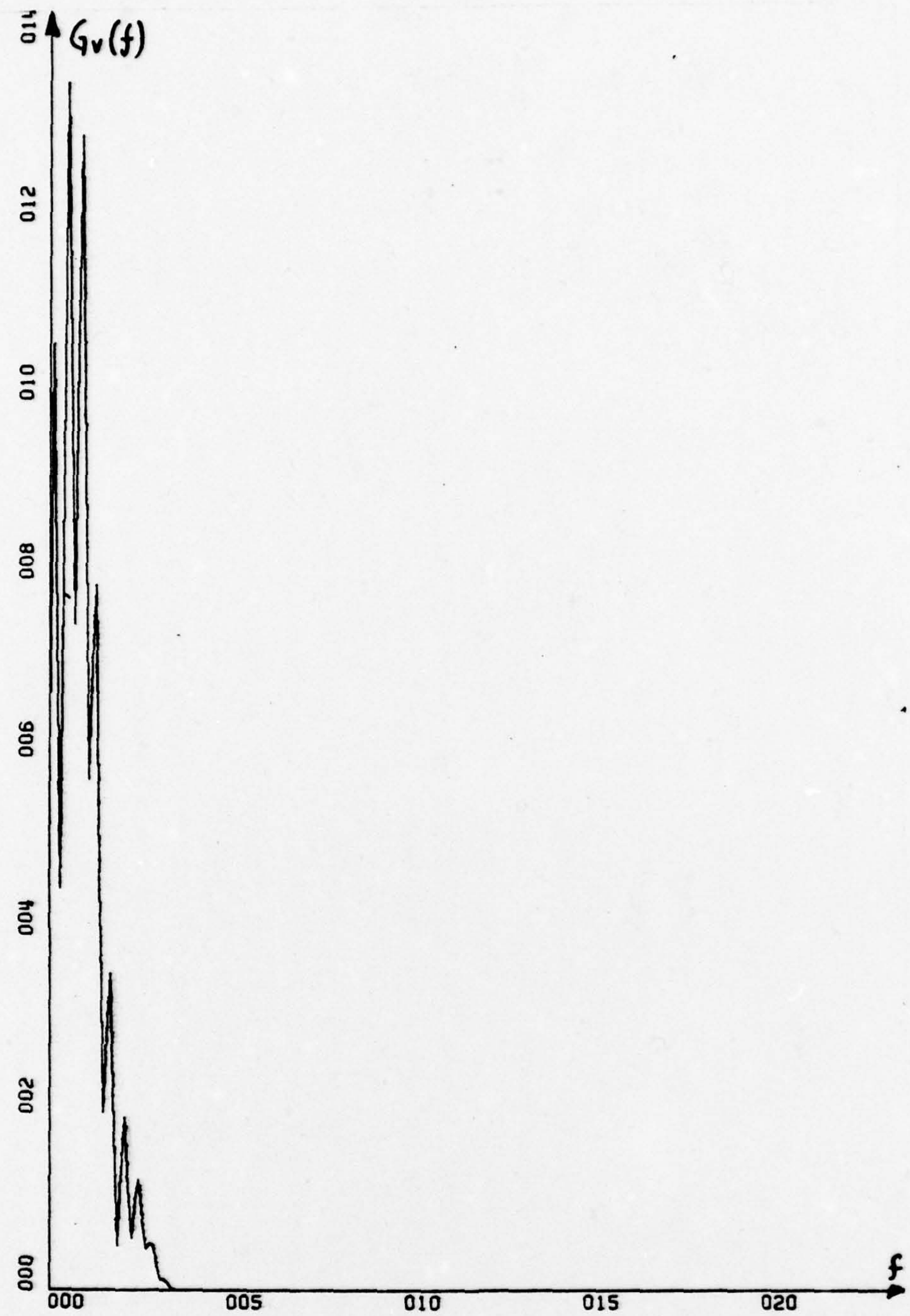


X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.

Fig. 36a. THE RAISED SINE SHAPE SEQUENCE 20X.

X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=5.00E+01 UNITS INCH.

Fig. 36b. THE ACF OF THE RAISED SINE SHAPE SEQUENCE 20X.



X-SCALE=5.00E+01 UNITS INCH.
Y-SCALE=2.00E+01 UNITS INCH.

Fig. 36c. THE POWER SPECTRUM OF THE RAISED SINE SHAPE SEQUENCE 20X.

APPENDIX C

EXPERIMENTAL SYSTEM

1. In this appendix, we present the experimental system used to verify the computer results. With this technique, it is possible to generate a variety of pulse shapes. Of particular interest are the raised-sine, triangular and ramp shaped elements of the sequence.

Included here are the results (photographs of the ACF's and spectra) of the experimental effort. The block diagram of the system is shown as Fig. 14 in Section III.D of this report.

The technique involves formation of the product of the desired sequence and synchronized available waveshapes using an Analog Voltage Multiplier (AVM). Then, the resulting "shaped" sequence ACF and power spectra are obtained using a commercial correlator and spectrum analyzer.

2. The Waveforms Generator.

In this project the IEC F-54A Function Generator provides the waveforms used to shape the sequences.

This unit provides the following pulse shapes over a frequency range from 0.005 Hz to 11 MHz:

* Sine wave
* Square wave
* Triangular wave
* Ramp (15/85 duty cycle) wave

* Fixed pulse (15% duty cycle)
* Rectangular pulse with continuously variable duty cycle (100 nsec. minimum pulse width).
* Sweep sawtooth waveforms.

The function generator's SYNC-OUT connection is used as clock for the sequence generator. This clock provides the required synchronization.

Through the DC OFFSET control the bipolar functions become unipolar which is a required input to the AVM. The voltage level is accordingly adjusted by the amplitude control.

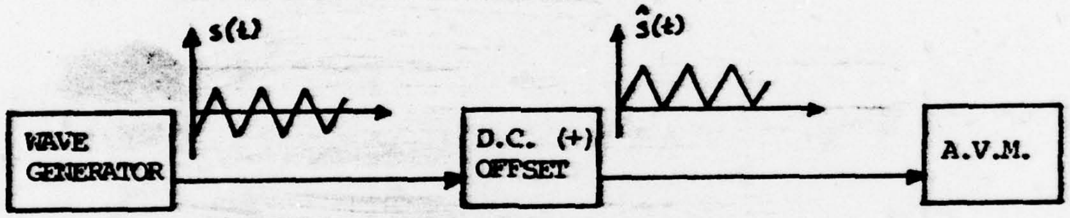


Fig. 37

THE D.C. OFFSET EFFECT AT THE OUTPUT OF THE FUNCTION GENERATOR

The SYNC-OUT connection of the function generator provides a bipolar pulse train, the amplitude of which (±1 volts) is insufficient as clock for the TTL feed-back shift registers of the sequence generator. Figure 38 shows the circuitry of the transistor amplifier used to obtain

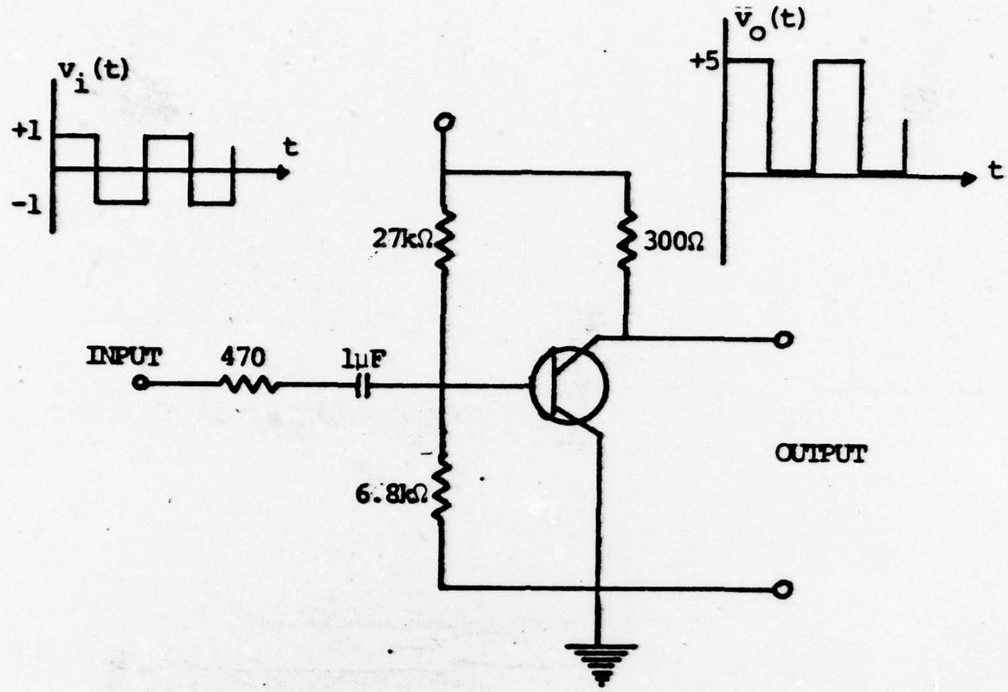


Fig. 38. THE CLOCK AMPLIFIER CIRCUIT DIAGRAM

a unipolar pulse train of 0-5 volts suitable for TTL logic.

Fig. 39 shows a photograph of both input and output of the amplifier.

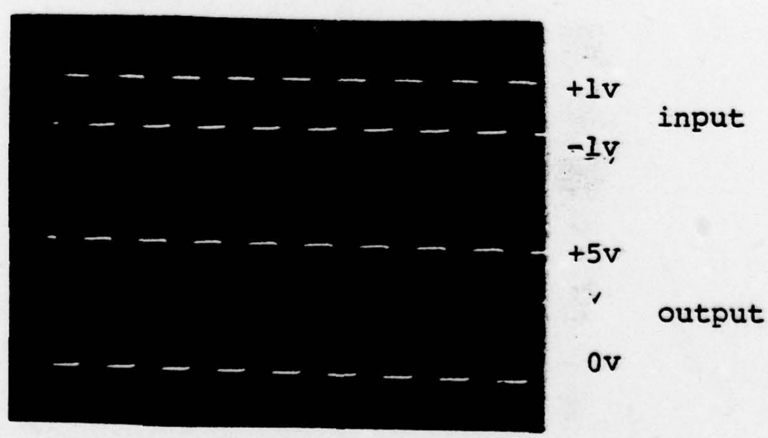


Fig. 39: PHOTOGRAPH OF THE INPUT AND OUTPUT OF THE CLOCK AMPLIFIER

3. m-Sequence Generator

The m-sequence generator in Fig. 14 is clocked by the amplified SYNC-OUT connection of the function generator and consists of a variable length shift-register and a modulo-two adder, using TTL logic.

a. Operation

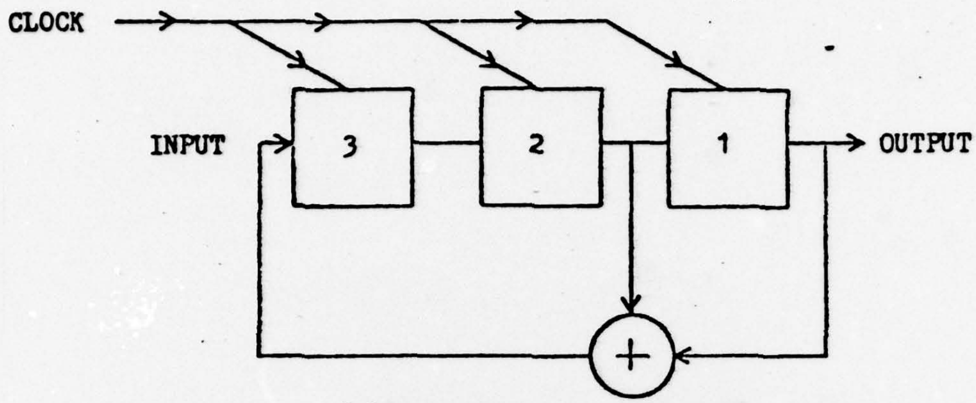
m- sequences are generated by selectively summing the outputs of Shift-Register positions and using this sum as the shift-register's input. A shift register m-sequence generator of length 3 is shown in 40a. Each time a clock pulse occurs, the outputs of register positions 1 and 2 are modulo-two summed and fedback to the input of register position 3.

Figure 40b shows the state of the shift register flip-flops for successive clock pulses; after $2^3-1 = 7$ pulses the sequence repeats itself. It should be noted that the shift-register takes on all possible states except the "000" state (terminal state).

b. Circuit Description

The m-sequence generator consists of one plug-in circuit board (DD-1 Digi-Designer) which provides the necessary power supply (5 volts and ground) for the operation of the gates, two shift registers (74164), one quad 2-input XOR Gate (7486) and the necessary circuitry.

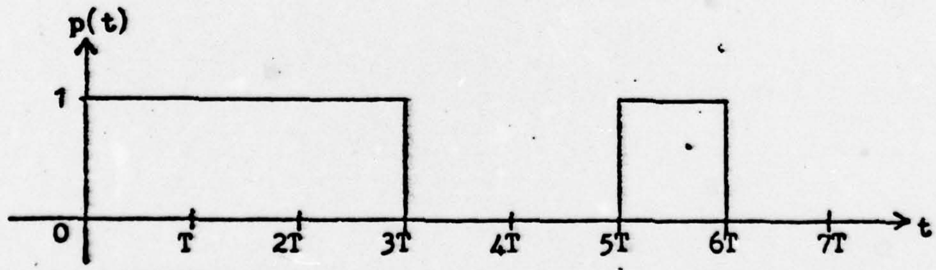
Component layout for the PN Generator is shown in Fig. 41. The 5 volts clock pulses are provided by the IEC function generator through the transistor amplifier.



(a) Shift Register Circuit

CLOCK PULSE	REGISTER STATE
1	1 1 1
2	0 1 1
3	0 0 1
4	1 0 0
5	0 1 0
6	1 0 1
7	1 1 0
8	1 1 1

(b) Shift Register State Transition



c) Output m-sequence.

Fig. 40. GENERATION OF AN m-SEQUENCE.

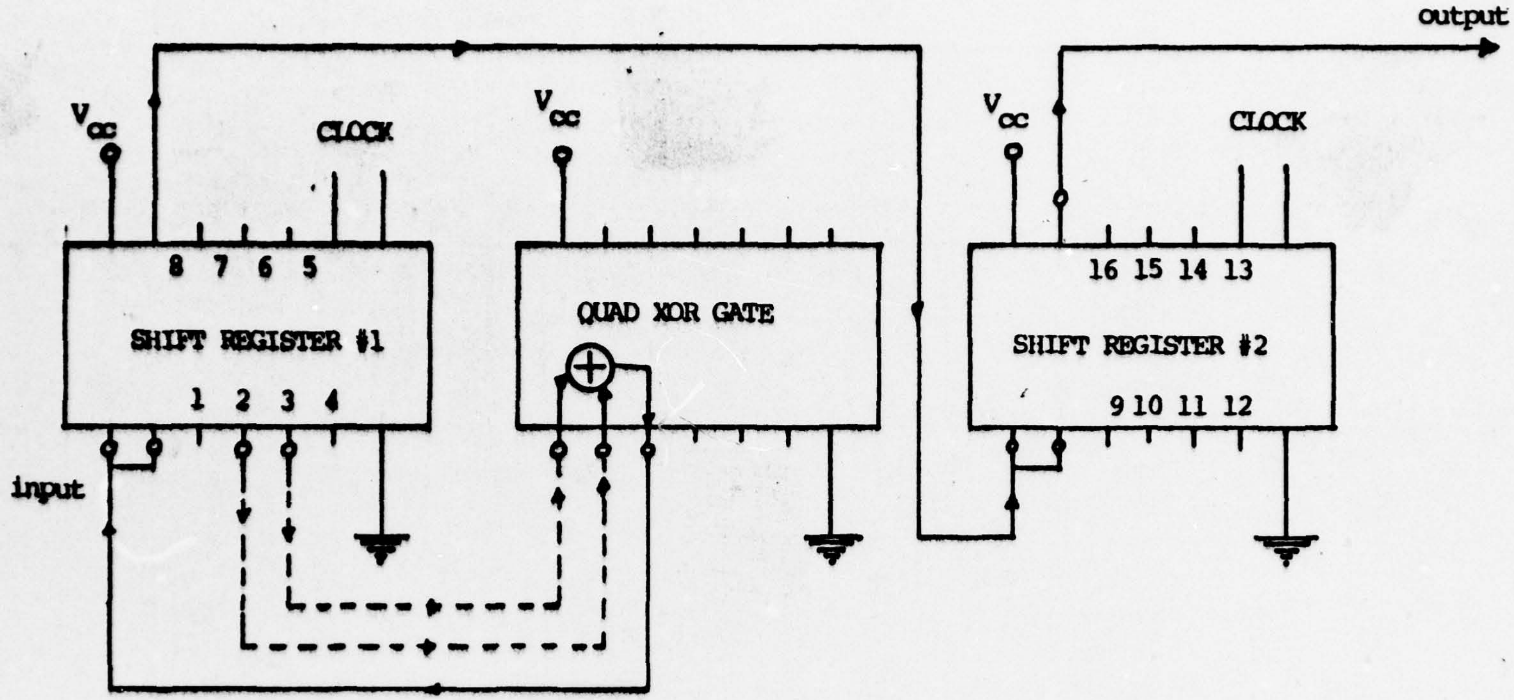


Fig. 41. m-SEQUENCE GENERATOR CIRCUIT DIAGRAM.
The dotted line denotes variable connection.

The m-sequence generator is wired to provide a variable length shift-register of 16 bits maximum, generating thus many linear sequences of length up to $L = 2^{16}-1 = 65,535$.

In Tables II and III the feedback connections for linear m-sequences are shown.

The generated m-sequences have an amplitude level of 5 volts and are unipolar. Since for the multiplication by the AVM, bipolar level is required, a negative DC offset is provided, with the use of a DC source of -2 volts. Thus, a voltage divider is formed and Fig. 42 shows the circuitry used as well as the calculated output V_2, for input V_1.

If Fig. 43 a photograph of the corresponding input and output of the negative DC offset is shown.

Thus, the required bipolar m-sequence input to the AVM is obtained.

TABLE II. ILLUSTRATED SHIFT-REGISTER CONNECTIONS OF 2 THROUGH 16 STAGES

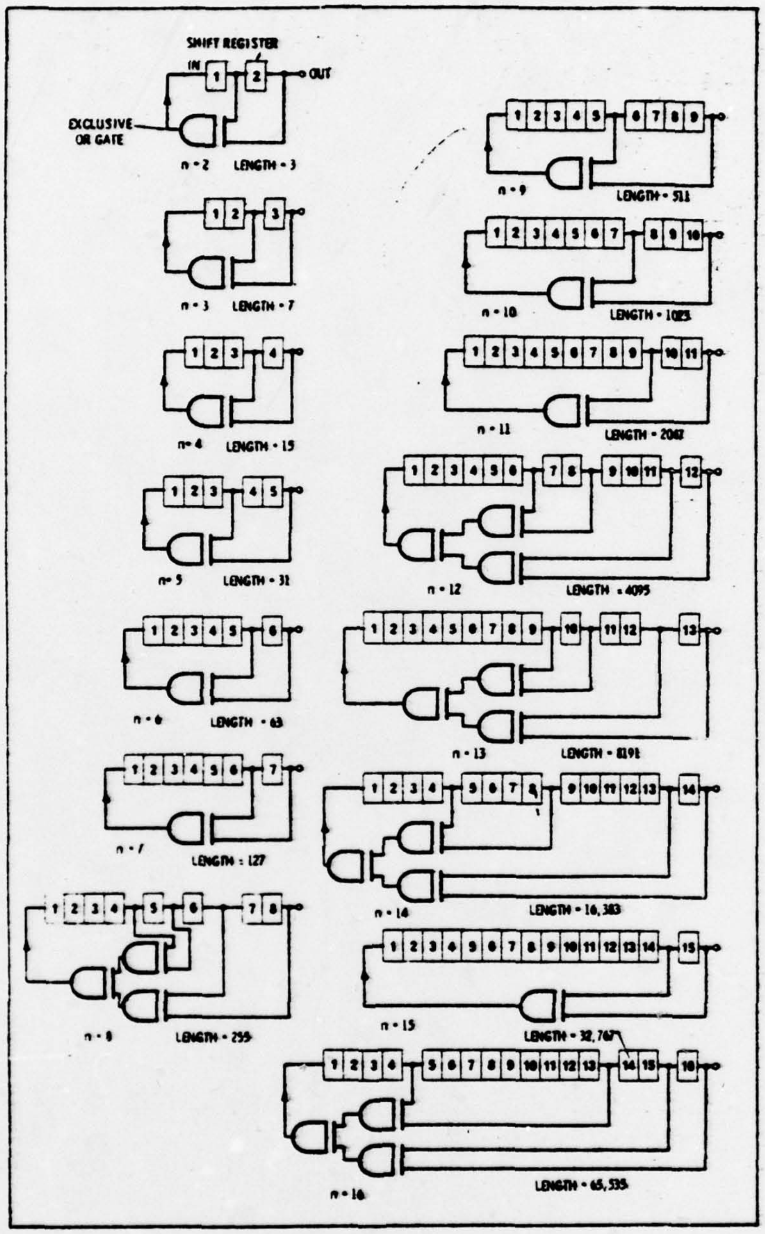


TABLE III. SHIFT REGISTER CONNECTIONS FOR m-SEQUENCES GENERATION

Number of Stages	Code Length	Maximal Taps
2*	3	[2, 1]
3*	7	[3, 1]
4	15	[4, 1]
5*	31	[5, 2] [5, 4, 3, 2] [5, 4, 2, 1]
6	63	[6, 1] [6, 5, 2, 1] [6, 5, 3, 2]
7*	127	[7, 1] [7, 3] [7, 3, 2, 1] [7, 4, 3, 2] [7, 6, 4, 2] [7, 6, 3, 1] [7, 6, 5, 2] [7, 6, 5, 4, 2, 1] [7, 5, 4, 3, 2, 1]
8	255	[8, 4, 3, 2] [8, 6, 5, 3] [8, 6, 5, 2] [8, 5, 3, 1] [8, 6, 5, 1] [8, 7, 6, 1] [8, 7, 6, 5, 2, 1] [8, 6, 4, 3, 2, 1]
9	511	[9, 4] [9, 6, 4, 3] [9, 8, 5, 4] [9, 8, 4, 1] [9, 5, 3, 2] [9, 8, 6, 5] [9, 8, 7, 2] [9, 6, 5, 4, 2, 1] [9, 7, 6, 4, 3, 1] [9, 8, 7, 6, 5, 3]
10	1023	[10, 3] [10, 8, 3, 2] [10, 4, 3, 1] [10, 8, 5, 1] [10, 8, 5, 4] [10, 9, 4, 1] [10, 8, 4, 3] [10, 5, 3, 2] [10, 5, 2, 1] [10, 9, 4, 2]
11	2047	[11,1] [11, 8, 5, 2] [11, 7, 3, 2] [11, 5, 3, 5] [11, 10, 3, 2] [11, 6, 5, 1] [11, 5, 3, 1] [11, 9, 4, 1] [11, 8, 6, 2] [11, 9, 8, 3]
12	4095	[12, 6, 4, 1] [12, 9, 3, 2] [12, 11, 10, 5, 2, 1] [12, 11, 6, 4, 2, 1] [12, 11, 9, 7, 6, 5] [12, 11, 9, 5, 3, 1] [12, 11, 9, 8, 7, 4] [12, 11, 9, 7, 6, 5] [12, 9, 8, 3, 2, 1] [12, 10, 9, 8, 6, 2]
13*	8191	[13, 4, 3, 1] [13, 10, 9, 7, 5, 4] [13, 11, 8, 7, 4, 1] [13, 12, 8, 7, 6, 5] [13, 9, 8, 7, 5, 1] [13, 12, 6, 5, 4, 3] [13, 12, 11, 9, 5, 3] [13, 12, 11, 5, 2, 1] [13, 12, 9, 8, 4, 2] [13, 8, 7, 4, 3, 2]
14	16, 383	[14, 12, 2, 1] [14, 13, 4, 2] [14, 13, 11, 9] [14, 10, 6, 1] [14, 11, 6, 1] [14, 12, 11, 1] [14, 6, 4, 2] [14, 11, 9, 6, 5, 2]

(Continued)

TABLE III. CONTINUED

Number of Stages	Code Length	Maximal Taps
		[14, 13, 6, 5, 3, 1] [14, 13, 12, 8, 4, 1]
		[14, 8, 7, 6, 4, 2] [14, 10, 6, 5, 4, 1]
		[14, 13, 12, 7, 6, 3] [14, 13, 11, 10, 8, 3]
15	32, 767	[15, 13, 10, 9] [15, 13, 10, 1] [15, 14, 9, 2]
		[15, 1] [15, 9, 4, 1] [15, 12, 3, 1] [15, 10, 5, 4]
		[15, 10, 5, 4, 3, 2] [15, 11, 7, 6, 2, 1]
		[15, 7, 6, 3, 2, 1] [15, 10, 9, 8, 5, 3]
		[15, 12, 5, 4, 3, 2] [15, 10, 9, 7, 5, 3]
		[15, 13, 12, 10] [15, 13, 10, 2] [15, 12, 9, 1]
		[15, 14, 12, 2] [15, 13, 9, 6] [15, 7, 4, 1]
		[15, 4] [15, 13, 7, 4]
16	65, 535	[16, 12, 3, 1] [16, 12, 9, 6] [16, 9, 4, 3]
		[16, 12, 7, 2] [16, 10, 7, 6] [16, 15, 7, 2]
		[16, 9, 5, 2] [16, 13, 9, 6] [16, 15, 4, 2]
		[16, 15, 9, 4]
17*	131, 071	[17, 3] [17, 3, 2, 1] [17, 7, 4, 3]
		[17, 16, 3, 1] [17, 12, 6, 3, 2, 1]
		[17, 8, 7, 6, 4, 3] [17, 11, 8, 6, 4, 2]
		[17, 9, 8, 6, 4, 1] [17, 16, 14, 10, 3, 2]
		[17, 12, 11, 8, 5, 2]
18	262, 143	[18, 7] [18, 10, 7, 5] [18, 13, 11, 9, 8, 7, 6, 3]
		[18, 17, 16, 15, 10, 9, 8, 7]
		[18, 15, 12, 11, 9, 8, [illegible], 6]
19*	524, 287	[19, 5, 2, 1] [19, 13, 8, 5, 4, 3]
		[19, 12, 10, 9, 7, 3] [19, 17, 15, 14, 13, 12, 6, 1]
		[19, 17, 15, 14, 13, 9, 8, 4, 2, 1]
		[19, 16, 13, 11, 19, 9, 4, 1] [19, 9, 8, 7, 6, 3]
		[19, 16, 15, 13, 12, 9, 5, 4, 2, 1]
		[19, 18, 15, 14, 11, 10, 8, 5, 3, 2]
		[19, 18, 17, 16, 12, 7, 6, 5, 3, 1]
20	1, 048, 575	[20, 3] [20, 9, 5, 3] [20, 19, 4, 3]
		[20, 11, 8, 6, 3, 2] [20, 17, 14, 10, 7, 4, 3, 2]
21	2, 097, 151	[21, 2] [21, 14, 7, 2] [21, 13, 5, 2]
		[21, 14, 7, 6, 3, 2] [21, 8, 7, 4, 3, 2]
		[21, 10, 6, 4, 3, 2] [21, 15, 10, 9, 5, 4, 3, 2]
		[21, 14, 12, 7, 6, 4, 3, 2] [21, 20, 19, 18, 5, 4, 3, 2]

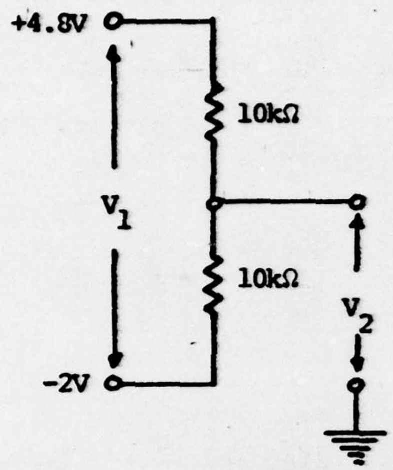
(Continued)

TABLE III. CONTINUED

Number of Stages	Code Length	Maximal Taps
22	4, 194, 303	[22, 1] [22, 9, 5, 1] [22, 20, 18, 16, 6, 4, 2, 1] [22, 19, 16, 13, 10, 7, 4, 1] [22, 17, 9, 7, 2, 1] [22, 17, 13, 12, 8, 7, 2, 1] [22, 14, 13, 12, 7, 3, 2, 1]
23	8, 388, 607	[23, 5] [23, 17, 11, 5] [23, 5, 4, 1] [23, 12, 5, 4] [23, 21, 7, 5] [23, 16, 13, 6, 5, 3] [23, 11, 10, 7, 6, 5] [23, 15, 10, 9, 7, 5, 4, 3] [23, 17, 11, 9, 8, 5, 4, 1] [23, 18, 16, 13, 11, 8, 5, 2]
24	16, 777, 215	[24, 7, 2] [24, 4, 3, 1] [24, 22, 20, 18, 16, 14, 11, 9, 8, 7, 5, 4] [24, 21, 19, 18, 17, 16, 15, 14, 13, 10, 9, 5, 4, 1]
25	33, 554, 431	[25, 3] [25, 3, 21] [25, 20, 5, 3] [25, 12, 4, 3] [25, 17, 10, 3, 2, 1] [25, 23, 21, 19, 9, 7, 5, 3] [25, 18, 12, 11, 6, 5, 4] [25, 20, 16, 11, 5, 3, 2, 1] [25, 12, 11, 8, 7, 6, 4, 3]
26	67, 108, 863	[26, 6, 2, 1] [26, 22, 21, 16, 12, 11, 10, 8, 5, 4, 3, 1]
27	134, 217, 727	[27, 5, 2, 1] [27, 18, 11, 10, 9, 5, 4, 3]
28	268, 435, 455	[28, 3] [28, 13, 11, 9, 5, 3] [28, 22, 11, 10, 4, 3] [28, 24, 20, 16, 12, 8, 4, 3, 2, 1]
29	536, 870, 911	[29, 2] [29, 20, 11, 2] [29, 13, 7, 2] [29, 21, 5, 2] [29, 26, 5, 2] [29, 19, 16, 6, 3, 2] [29, 18, 14, 6, 3, 2]
30	1, 073, 74, 1, 823	[30, 23, 2, 1] [30, 6, 4, 1] [30, 24, 20, 16, 14, 13, 11, 7, 2, 1]
31*	2, 147, 483, 647	[31, 29, 21, 17] [31, 28, 19, 15] [31, 3] [31, 3, 2, 1] [31, 13, 8, 3] [31, 21, 12, 3, 2, 1] [31, 20, 18, 7, 5, 3] [31, 30, 29, 25] [31, 28, 24, 10] [31, 20, 15, 5, 4, 3] [31, 16, 8, 4, 3, 2]
32	4, 294, 967, 295	[32, 22, 2, 1] [32, 7, 5, 3, 2, 1] [32, 28, 19, 18, 16, 14, 11, 10, 9, 6, 5, 1]
33	8, 589, 934, 591	[33, 13] [33, 22, 13, 11] [33, 26, 14, 10] [33, 6, 4, 1] [33, 22, 16, 13, 11, 8]
61*	2, 305, 843, 009, 213, 693, 951	[61, 5, 2, 1]
89*	618, 970, 019, 642, 690, 137, 449, 562, 112	[89, 6, 5, 3]

TABLE IV. CHARACTERISTICS OF MAXIMUM LENGTH SEQUENCES

Shift Register Length n	Sequence Period L	Number of Different Sequences Sequences	Shift Register Length n	Sequence Period L	Number of Different Sequences
2	3	1	12	4096	144
3	7	2	13	8191	630
4	15	2	14	16383	756
5	31	6	15	32767	1800
6	63	6	16	65535	2048
7	127	18	17	131071	7710
8	255	16	18	262143	7776
9	511	48	19	524287	27594
10	1023	60	20	1048575	24000
11	2047	176	21	2097151	84672



$$V_2 = V_1 \cdot \frac{10}{20}$$

$$= (4 \cdot 8) \cdot \frac{1}{2}$$

$$= 1.4 \text{ Volts p-p}$$

$$\text{or } = \pm 0.7 \text{ Volts}$$

Fig. 42. THE NEGATIVE D.C. OFFSET CIRCUIT DIAGRAM.

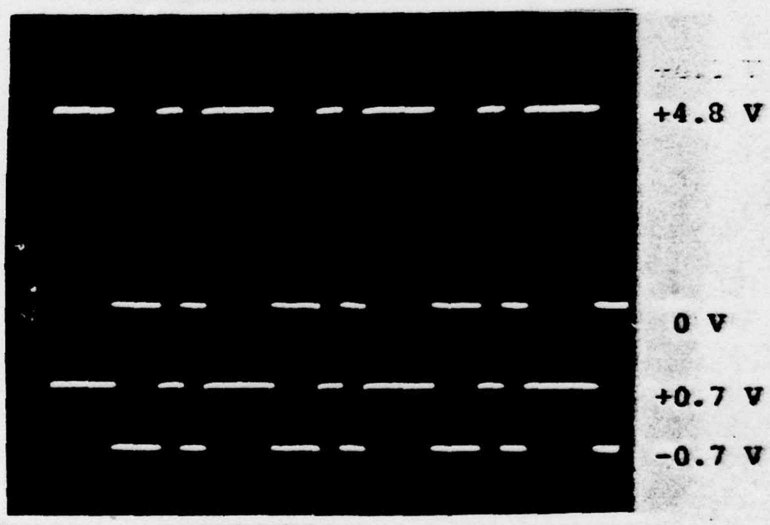


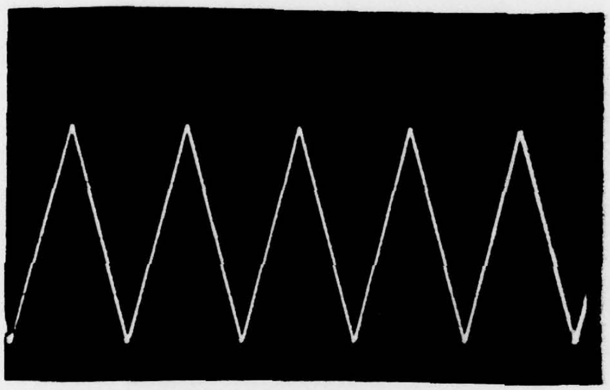
Fig. 43. THE INPUT AND OUTPUT OF THE NEGATIVE D.C. OFFSET

4. The AVM (Analog Voltage Multiplier)

Finally for the "shaping" of the generated sequences the principle of multiplication is used by which the sequence or code under examination is multiplied by the desired "shape" or function waveform , as already discussed.

For this purpose an AVM is used (Analog Devices Model 429A).

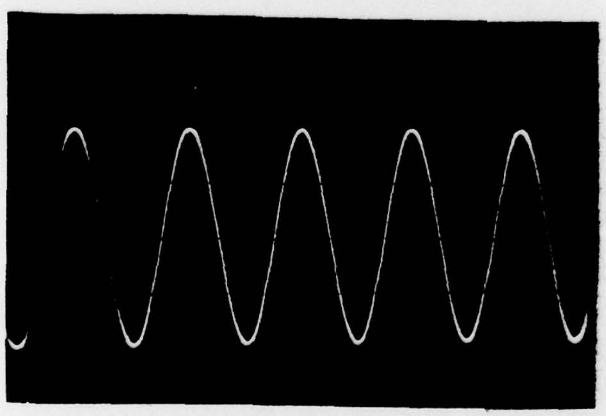
One input to the AVM is a unipolar "shaping" waveform, with variable amplitude and DC offset level. Fig. 44 shows photographs of the available shapes.



+7V

0V

(a) Triangle



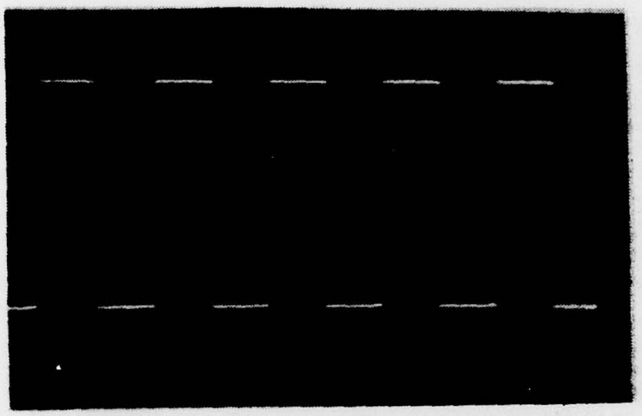
+7V

0V

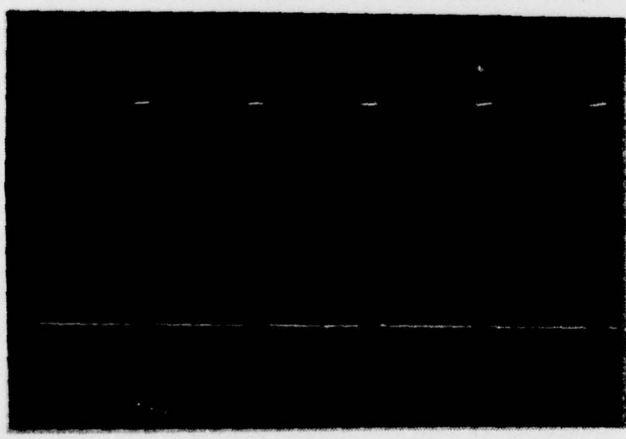
(b) Raised-sine

Fig. 44. PHOTOGRAPHS OF THE WAVESHAPES AT THE AVM INPUT.

(c) Ramp



(d) Rectangular (50% duty cycle)



(e) Rectangular (15% duty cycle)

Fig. 44. CONTINUED

The other AVM input is the bipolar sequence of constant amplitude level (± 0.7 volts) shown in Fig. 45.

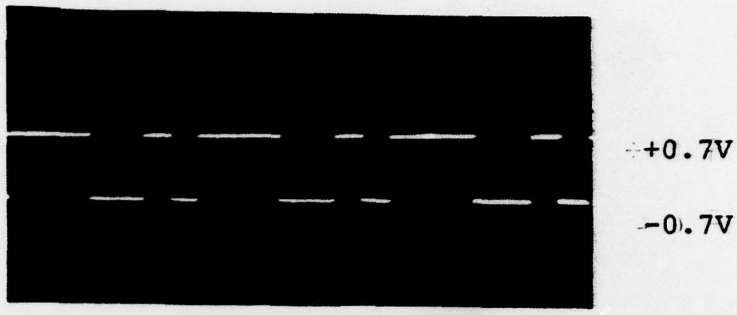


Fig. 45. PHOTOGRAPH OF THE 7-BIT m-SEQUENCE AT THE INPUT OF THE AVM

The resulting operation of the AVM is an Analog Amplitude Multiplication of the 2 inputs. The two traces of the photograph in Fig. 46 indicate the 2 waveforms are in phase at the input of the AVM.

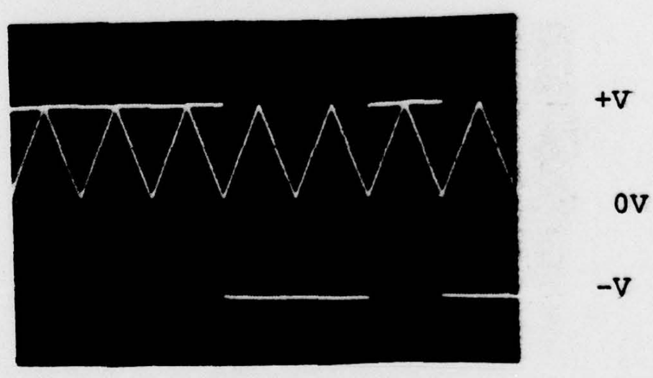
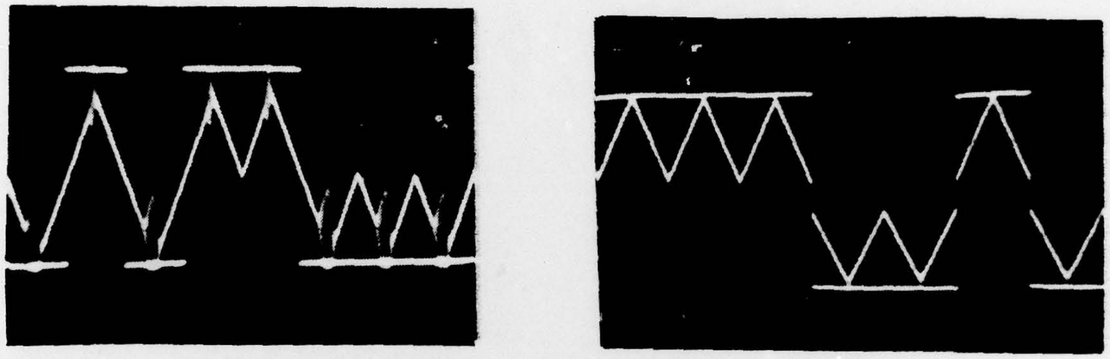


Fig. 46. PHOTOGRAPH OF THE m-SEQUENCE AND THE SHAPING WAVEFORMS AT THE INPUT OF THE AVM

The vertical scale is adjusted to demonstrate the synchronized condition.

Figures 47(a) and 47(b) show possible irregular results at the output of the AVM caused by improper adjustment of amplitude (Fig. 47a) or DC offset (Fig. 47b) of the waveform generator.



(a) (b)

Fig. 47. PHOTOGRAPHS OF POSSIBLE UNDESIRED OUTPUTS OF THE AVM

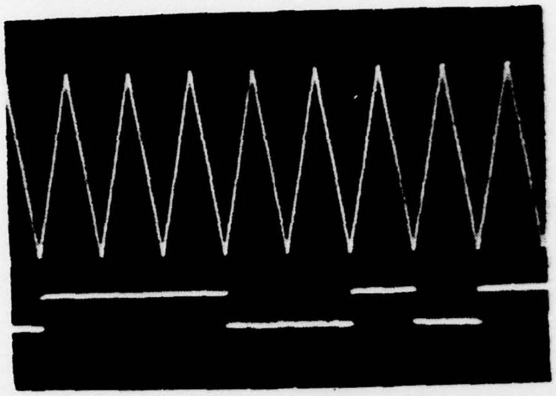
A final adjustment with respect to DC amplitude control knob and DC offset control of the desired waveform is required to obtain the highest undistorted amplitude. This provides the waveforms shown in Fig. 15b of Section III.D.2.

The output after final adjustment has an undistorted amplitude of $\pm$ 0.5 volts obtained as follows:

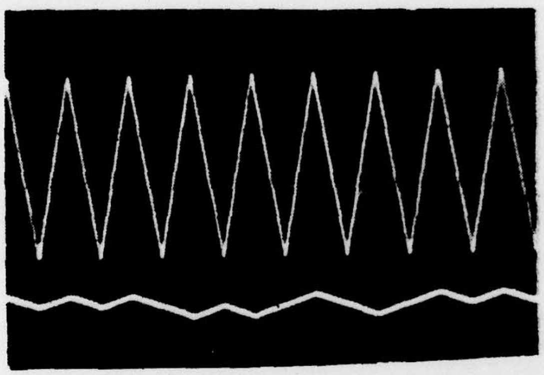
a) waveform level: +7 volts

b) sequence level: +0.7 or −0.7 volts

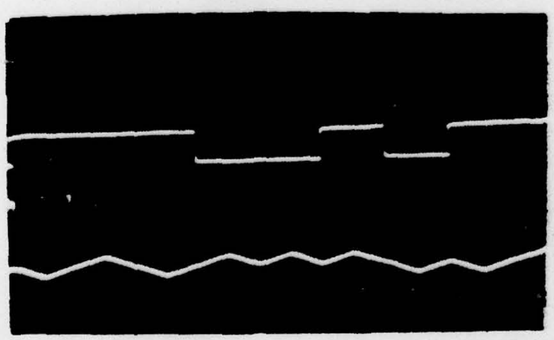
c) multiplier characteristic: $7 \times \pm 0.7/10 \cong \pm 0.5$ volts.



(a) AVM inputs



(b) AVM output and one input



(c) AVM output and the other input

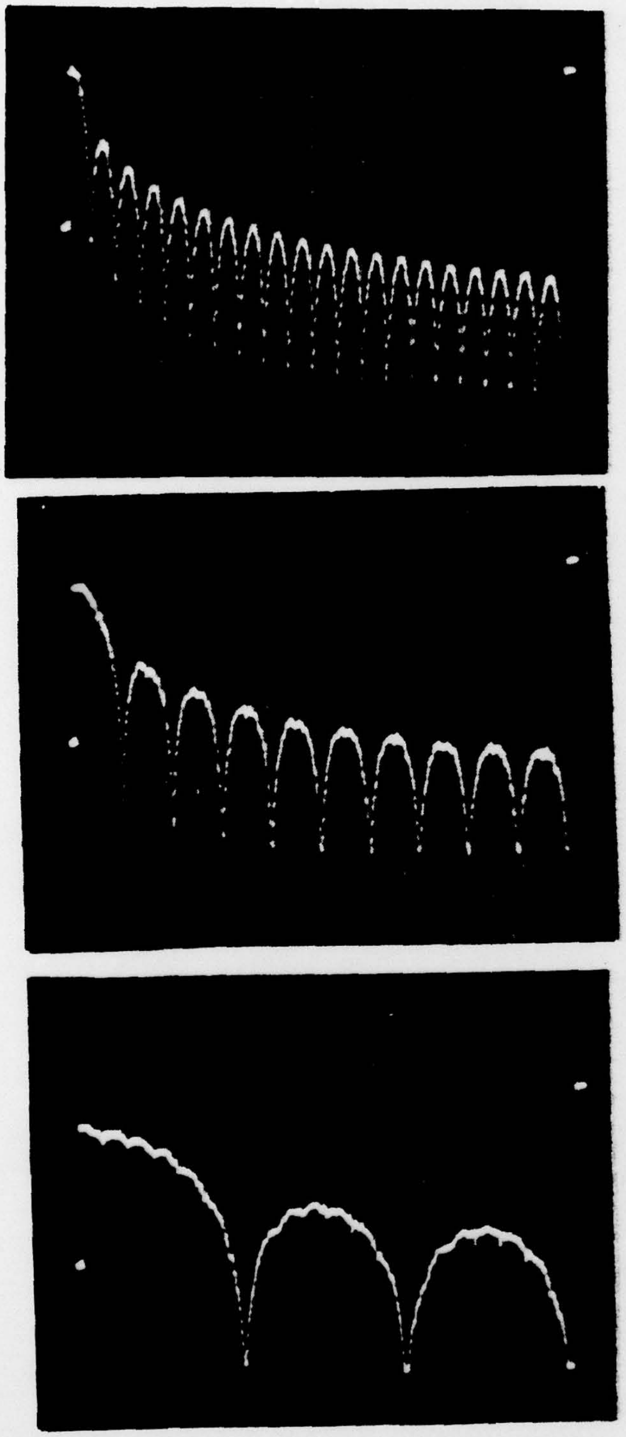
Fig. 48. COMPARISON OF INPUTS AND OUTPUTS OF THE AVM

A comparison between the 2 inputs and between either the sequence, or the waveform with the resulting "shaped" sequence can be made by observing Figures 48(a), (b) and (c) under the same scale.

5. Spectrum Analysis

In this section additional photographs of the resulting spectra are presented. The spectra were obtained using a Spectral Dynamics SD-335 Spectrum Analyzer.

In Figures 49(a) through (f) the spectra of the 127-bit m-sequence are shown under various shapes and with a clock requency of 2.5 kHz. The display of the spectrum analyzer is logarithmic and the window is 50 kHz wide. In Figures 50(a) through (f) the spectra of the sequence of Fig. 49 are shown, but with clock frequency of 10 kHz. In Figures 51(a) through (c) the spectra of arbitrary sequences (not m-sequences) are shown with the original, triangular and raised-sine shapes. The clock frequency is 5 kHz, and the display is logarithmic. In Figures 52(a) through (c) the spectra of the sequence of Fig. 51 are shown but with linear display.

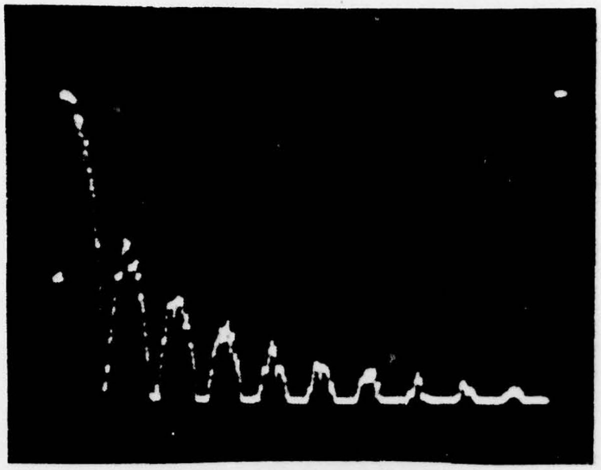


(a) Rectangular
(100% duty cycle)

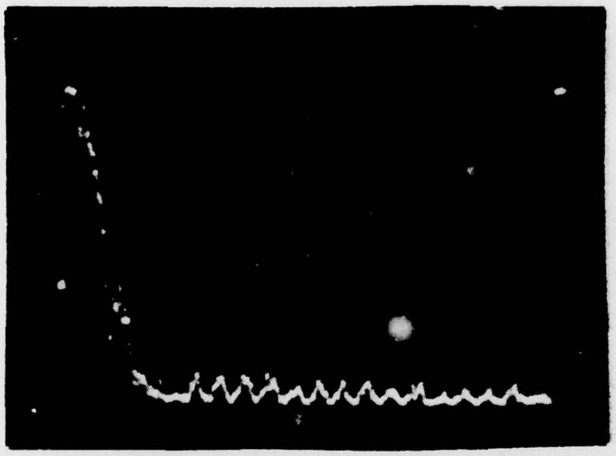
(b) Rectangular
(50% duty cycle)

(c) Rectangular
(15% duty cycle)

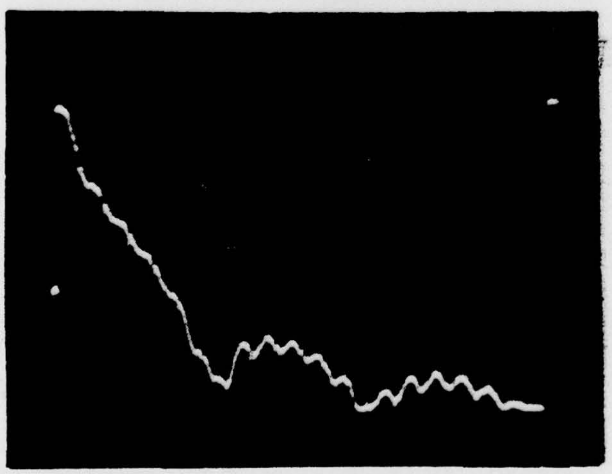
Fig. 49. THE AVERAGED SPECTRA OF THE 127-BIT m-SEQUENCE. Log-display, f = 2.5 kHz, 64 averages, 10 dB output gain, 50 kHz window.



(d) Triangle

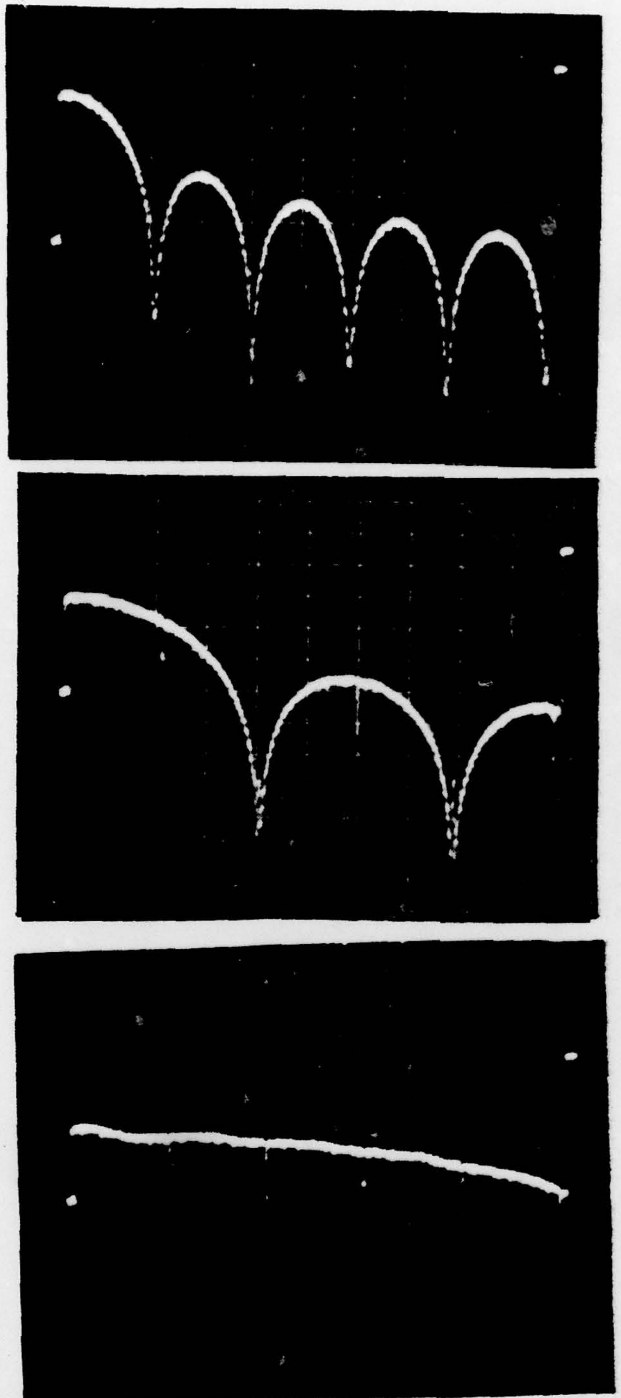


(e) Raised Sine



(f) Ramp

Fig. 49. CONTINUED

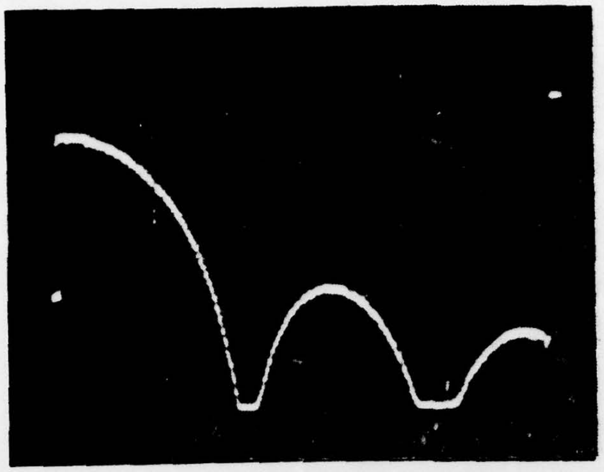


(a) Rectangular

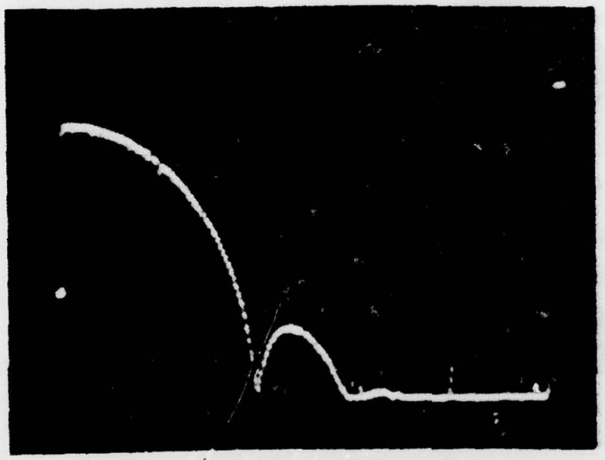
(b) 50% Duty Cycle

(c) 15% Duty Cycle

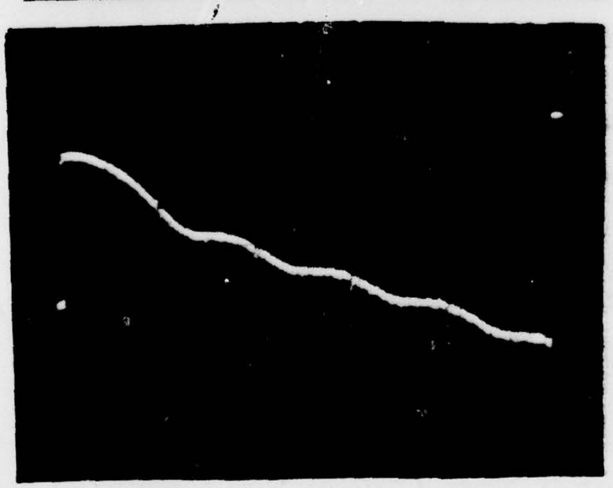
Fig. 50. THE AVERAGED SPECTRAL OF THE 127-BIT m-SEQUENCE. Log display, f = 10 kHz, 64 averages, 10 dB output gain, 50 kHz window.



(d) Triangle

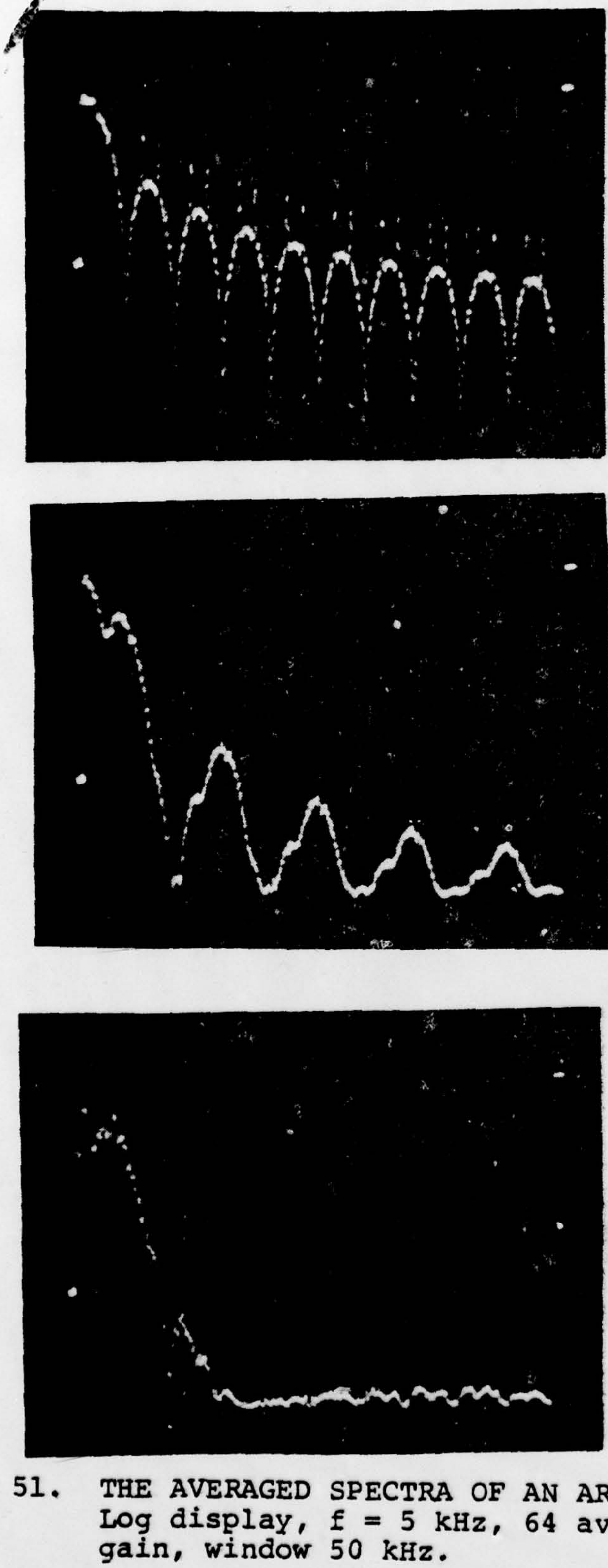


(e) Raised sine



(f) Ramp

Fig. 50. CONTINUED

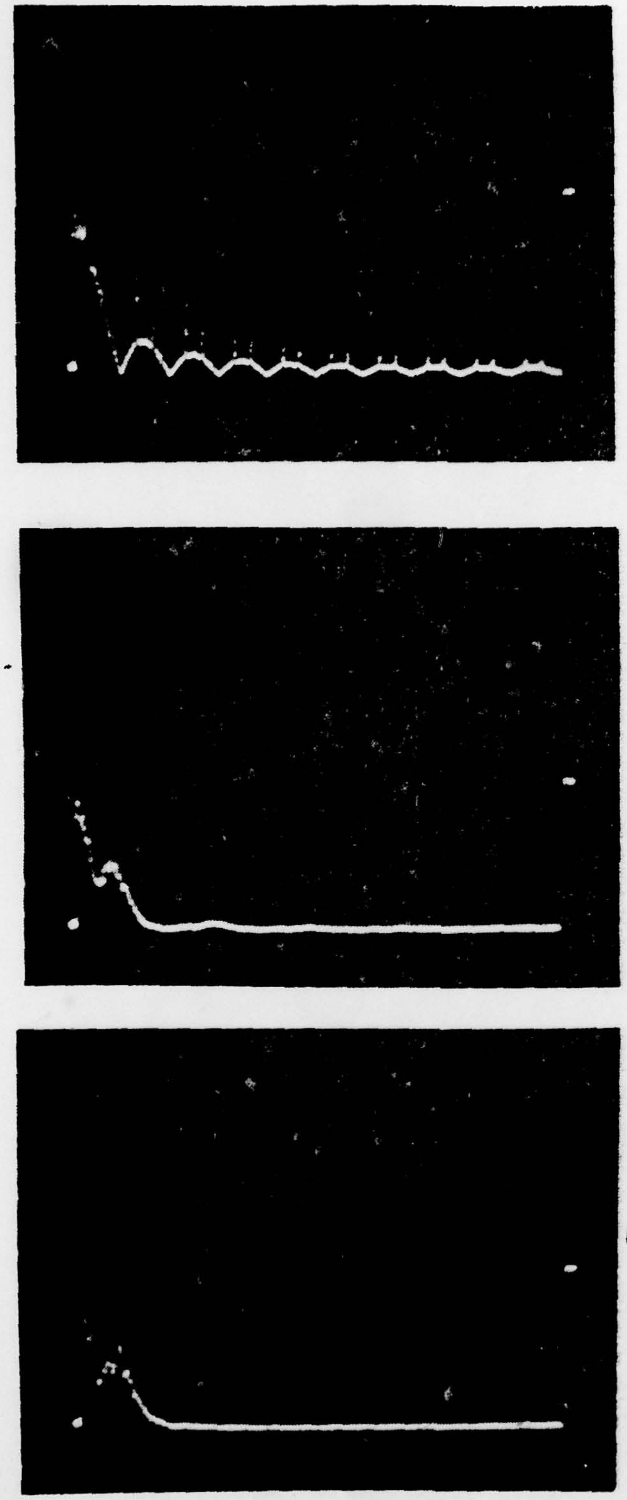


(a) Rectangular

(b) Triangle

(c) Raised sine

Fig. 51. THE AVERAGED SPECTRA OF AN ARBITRARY SEQUENCE. Log display, f = 5 kHz, 64 averages, 10 dB output gain, window 50 kHz.



(a) Rectangular

(b) Triangle

(c) Raised sine

Fig. 52. THE AVERAGED SPECTRA OF AN ARBITRARY SEQUENCE. Linear display, f = 5 kHz, 64 averages, 10 dB output gain, window 50 kHz.

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